Earth as a planet

Part 1: With Global Geophysics Towards the Origin of Life
Part 2: From the Evolution of Plate Tectonics to the Rise of O_2

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Petnica, Serbia
Workshop in Geology & Geophysics of the Solar System
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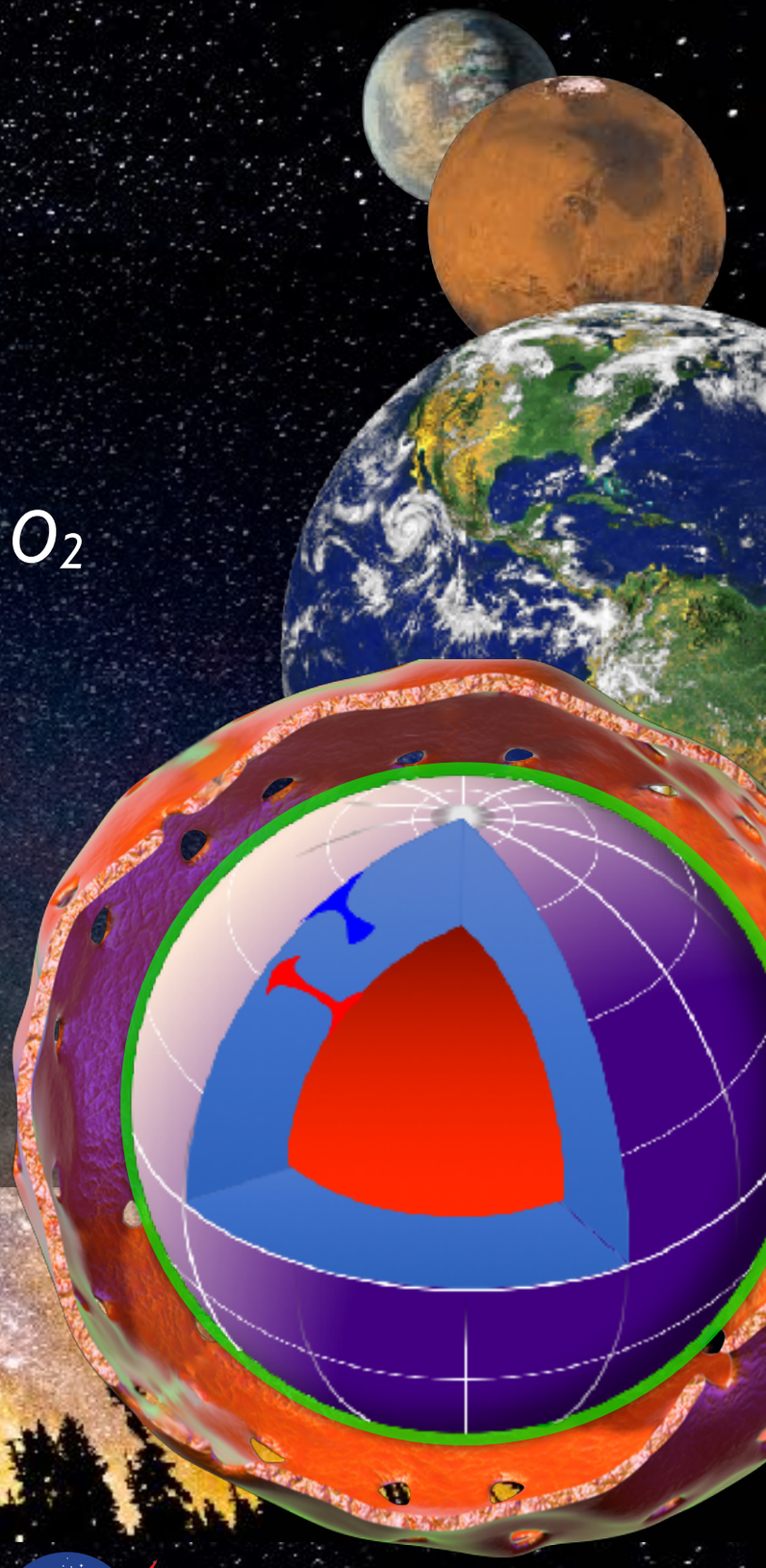

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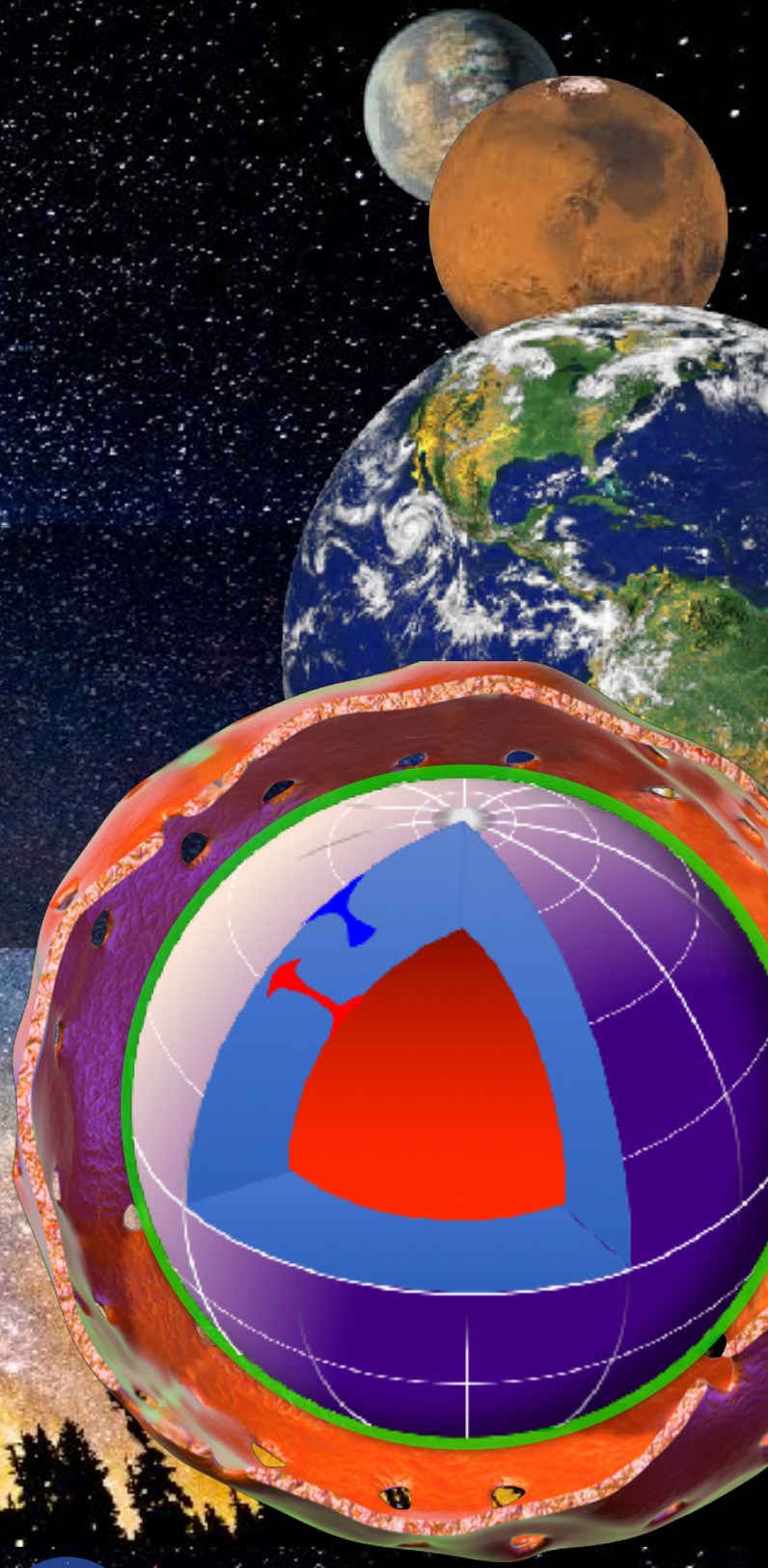
Part I: With Global Geophysics Towards the Origin of Life



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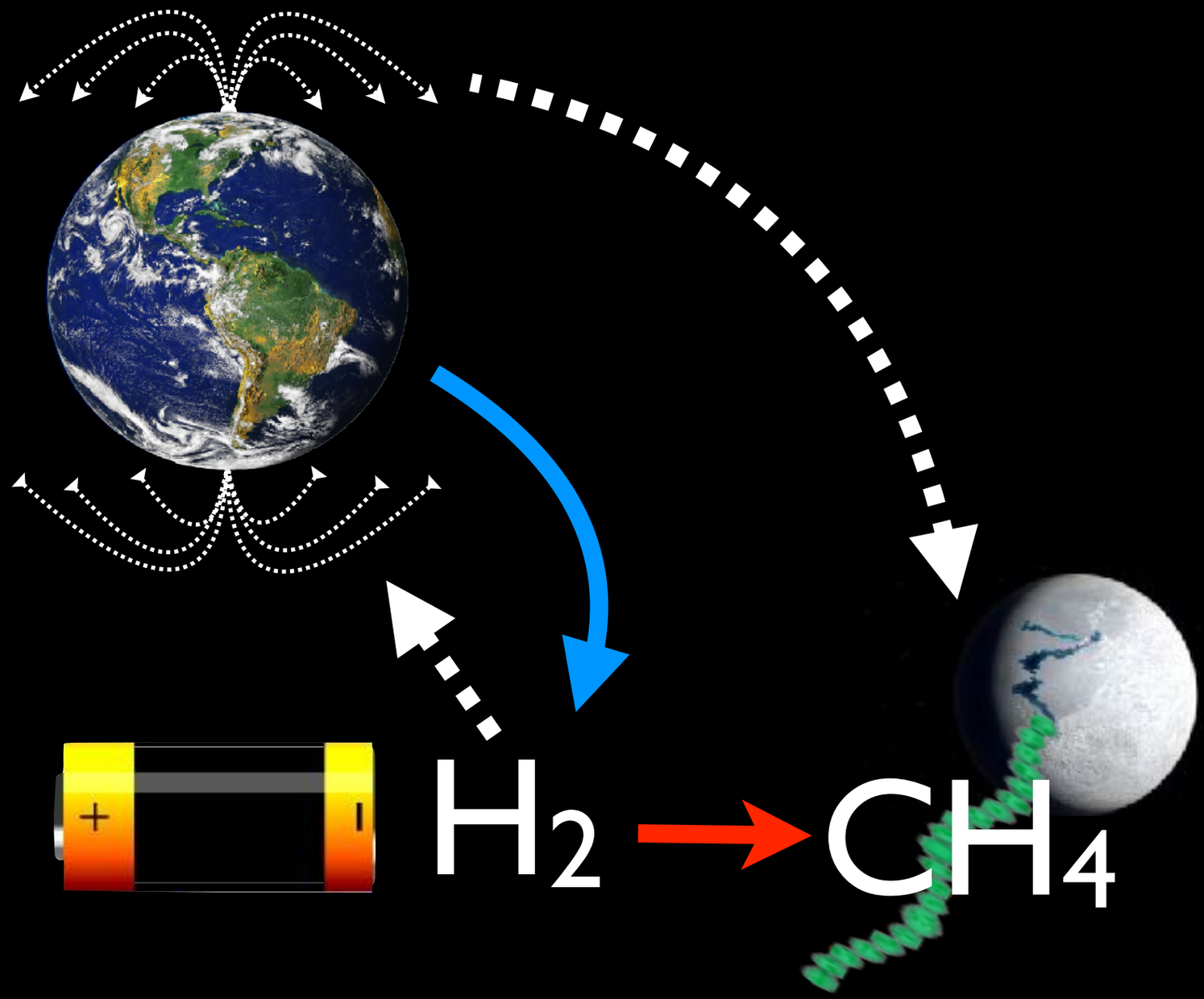
Part 1: Thermal Evolution, magnetic field & H_2

- *Heat transport*
- *Magnetic field*
- *Redox (r): H_2*



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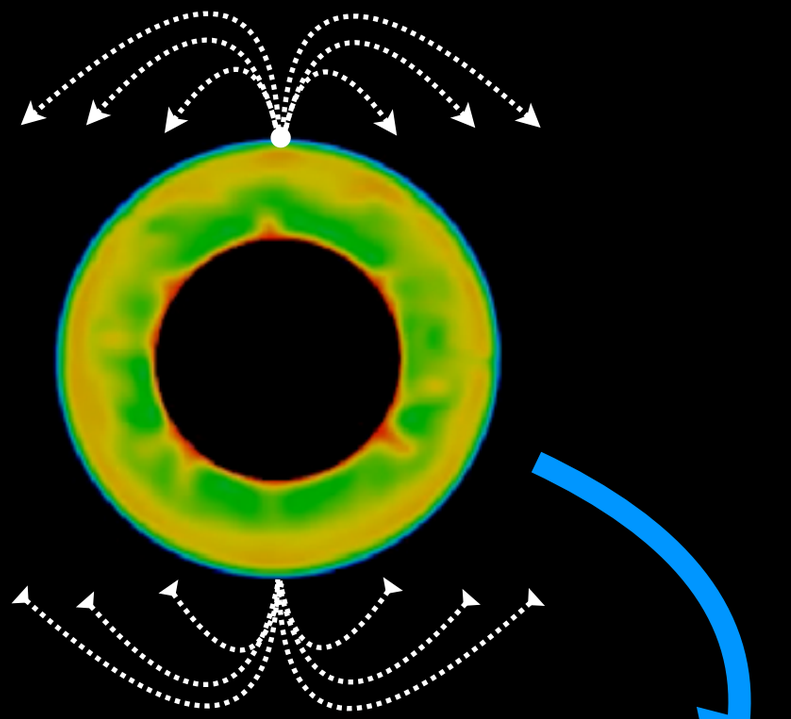
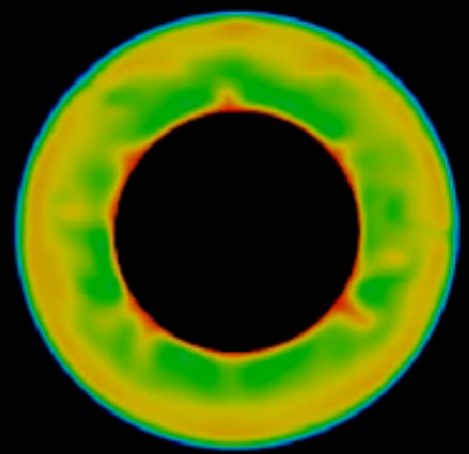


H_2

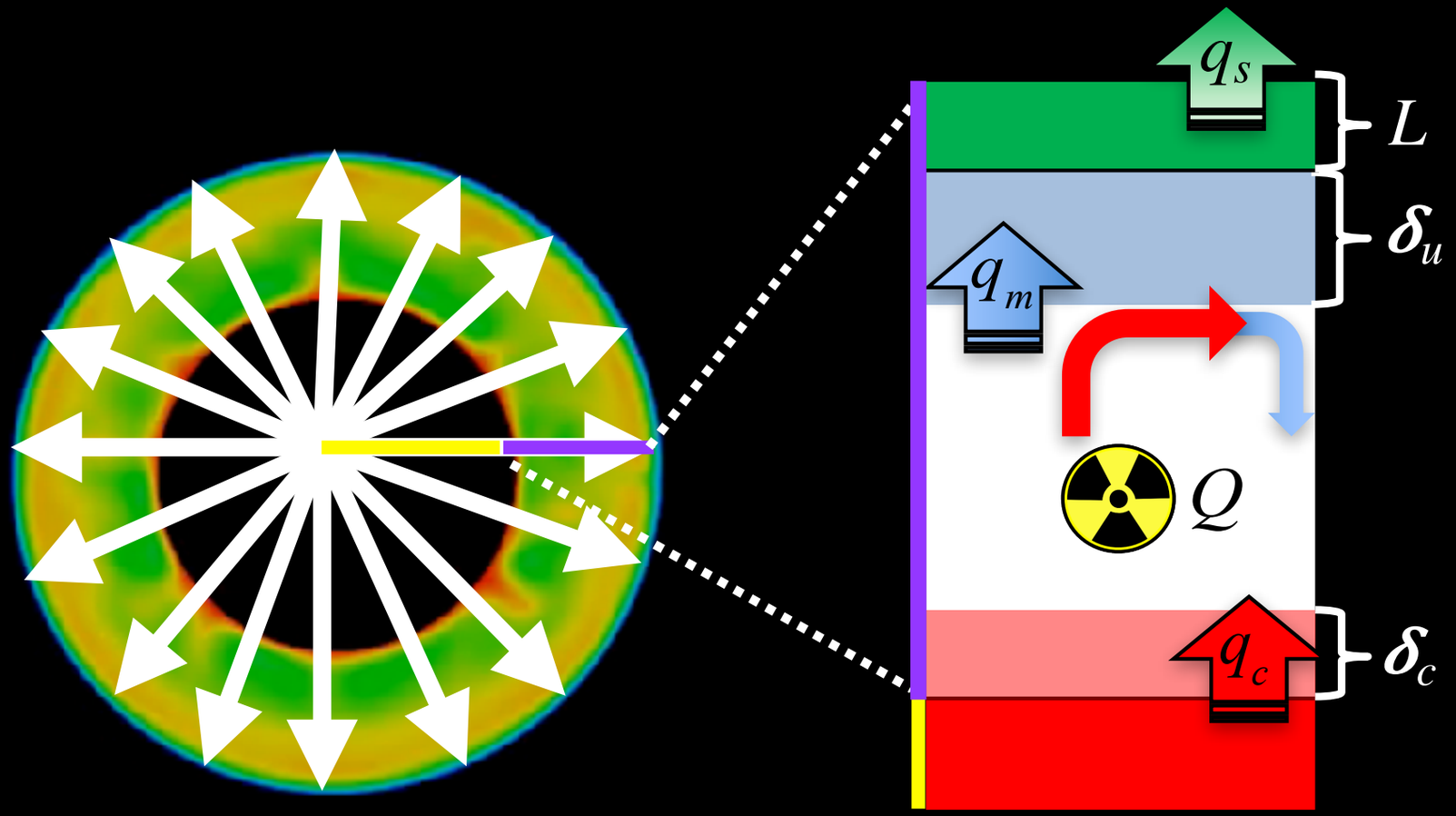
Thermal evolution models

- *Heat transport*



Thermal evolution models

- *Heat transport*

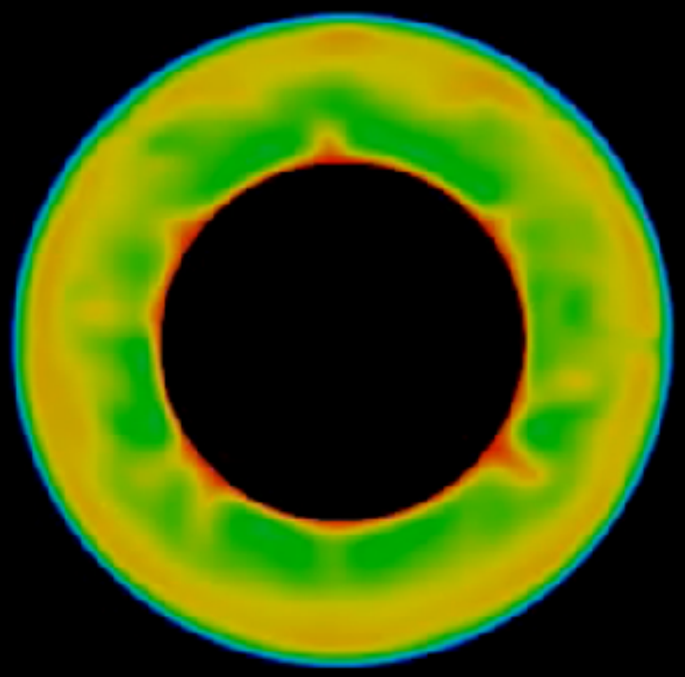


3D Parameterized Mantle Convection Model
2D/3D Mantle Convection Model
Stamenković + (2018 in prep)
e.g., Citcoms, GAIA, ...
Stamenković + (2012, 2016)

1D Parameterized Model
Stamenković + (2012, 2016),
Stamenković & Breuer (2014)

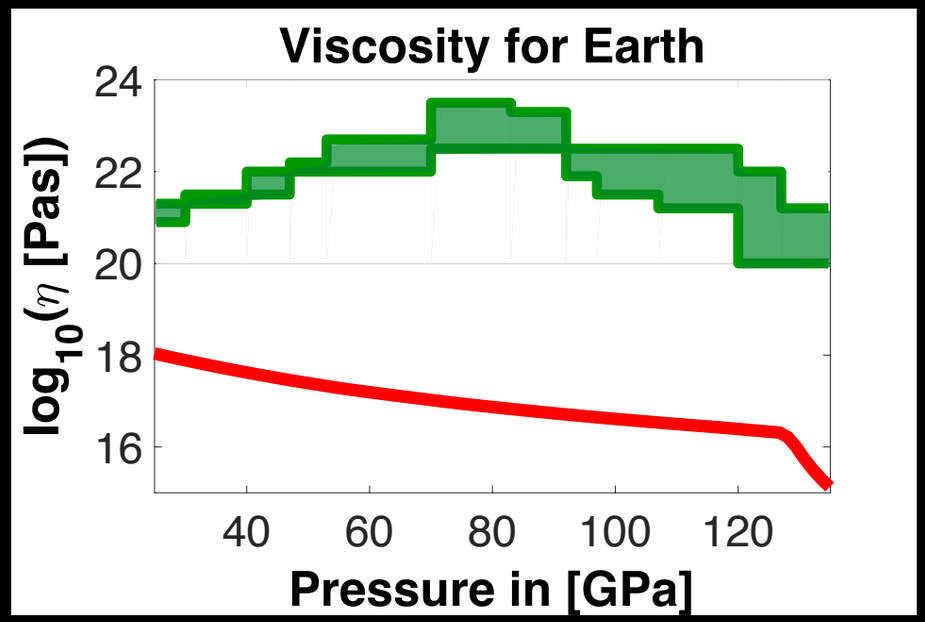
Viscosity controls heat flow

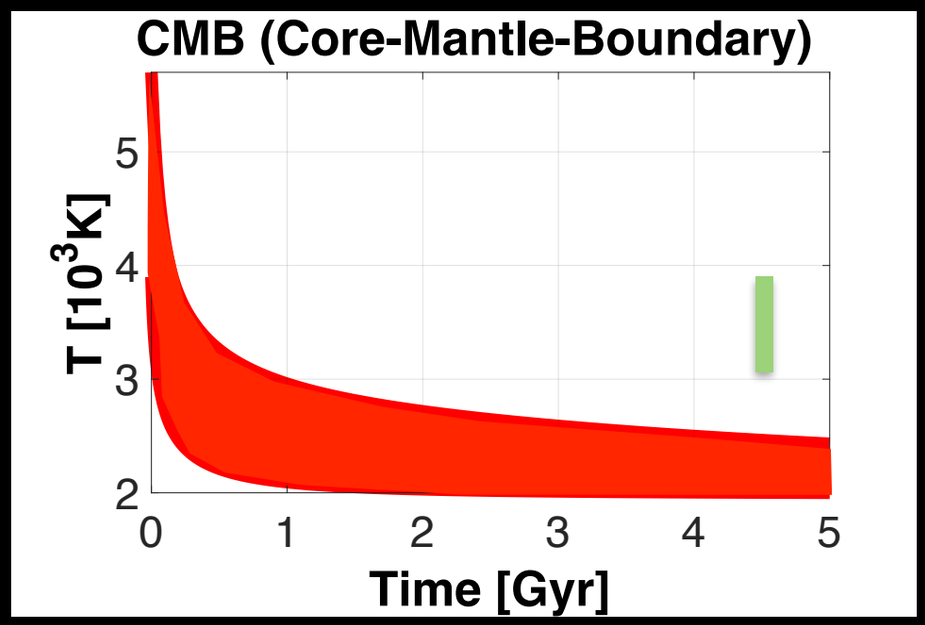
- *Heat transport*



"Classic" Earth: Viscosity is η(T)

- *Heat transport*
- *We need* η(T,P)





Stamenković + (2011, 2012)

Viscosity through melting curves

- *Heat transport*

$$\eta(P,T) = \frac{R_g d^m}{A m_{mol}} \cdot \frac{T \cdot \rho(P,T)}{D_{eff}(P,T)} = \frac{R_g d^m}{D_0 A m_{mol}} \cdot T \cdot \rho(P,T) \cdot \exp\left(\frac{H^*(P)}{R_g T}\right) \quad (1)$$

$$H^*(P) = \xi R_g T_{melt}(P) \quad (2)$$

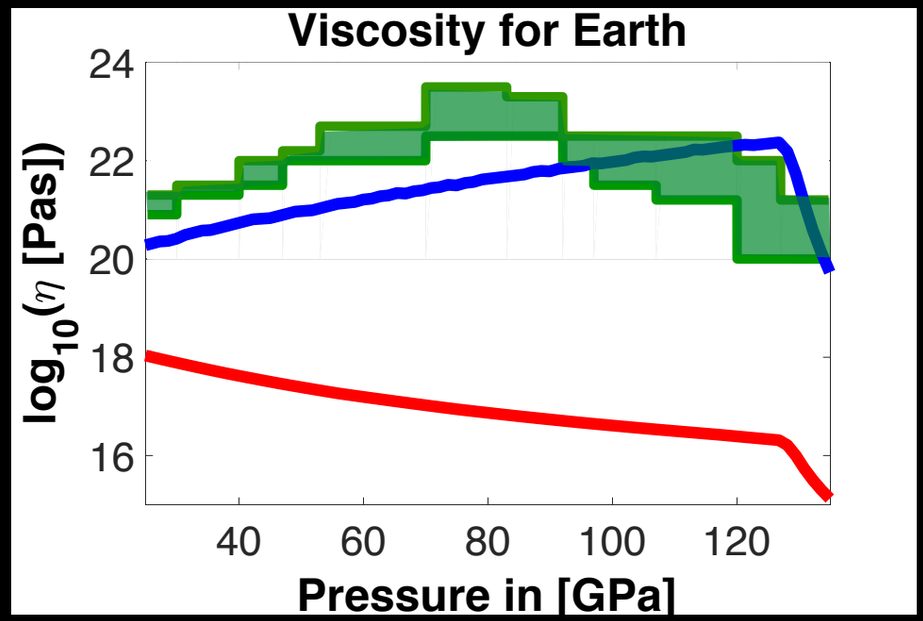
$$\frac{d\ln(T_{melt})}{dP} = \frac{2\gamma_\alpha}{K_T \cdot (1 + 2\gamma_\alpha \alpha T_{melt})} \approx \frac{2 \cdot (\gamma_\alpha - \Delta(P))}{K_T}, \quad (3)$$

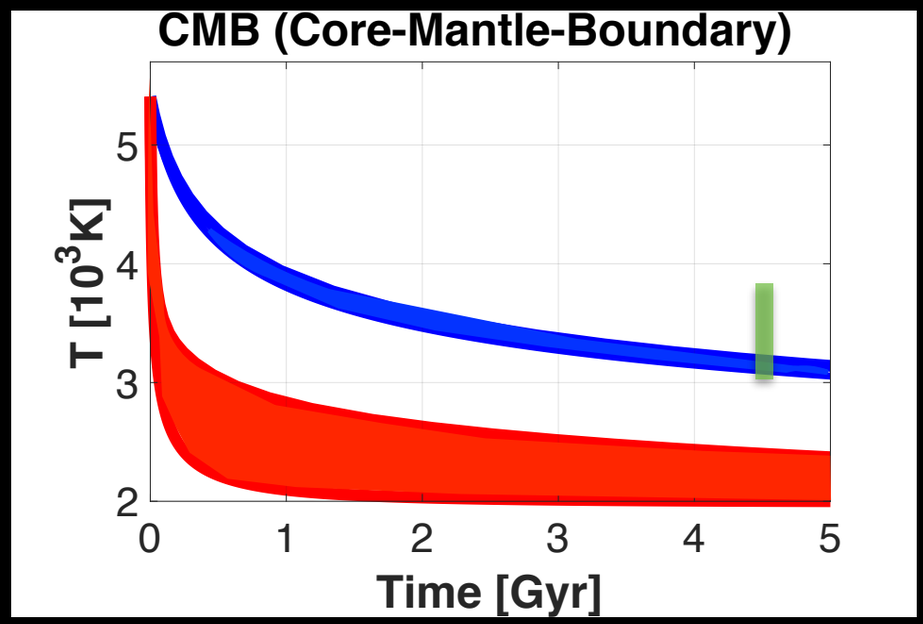
$$\gamma_\alpha(\rho,T) = \frac{\alpha K_T}{\rho C_V} = \frac{\alpha K_S}{\rho C_P} = \frac{\gamma_{vib}(\rho) - T m_{\Lambda H} a(\rho)}{1 - a(\rho) \cdot T} \quad (4)$$

Stamenković + (2011)

What has changed for the Earth with η(T,P)?

- *Heat transport*
  - *We can satisfy constraints*
  - *Longer melt (~Gyr)*
  - *What is the effect on the magnetic field?*

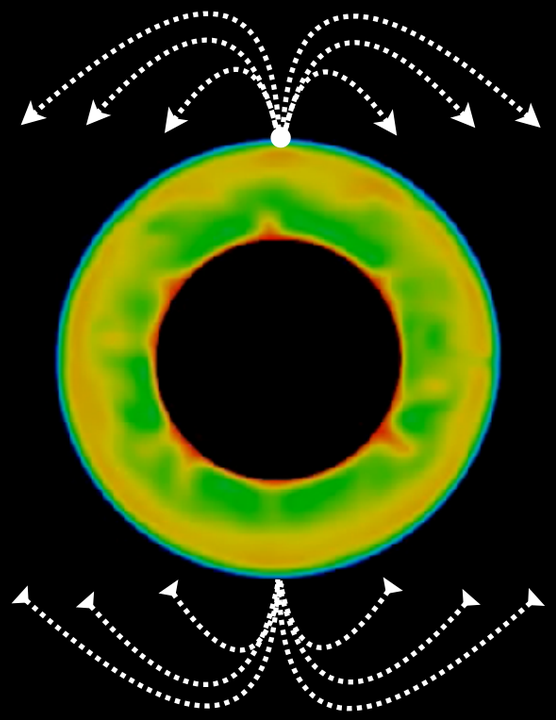




Stamenković + (2012)

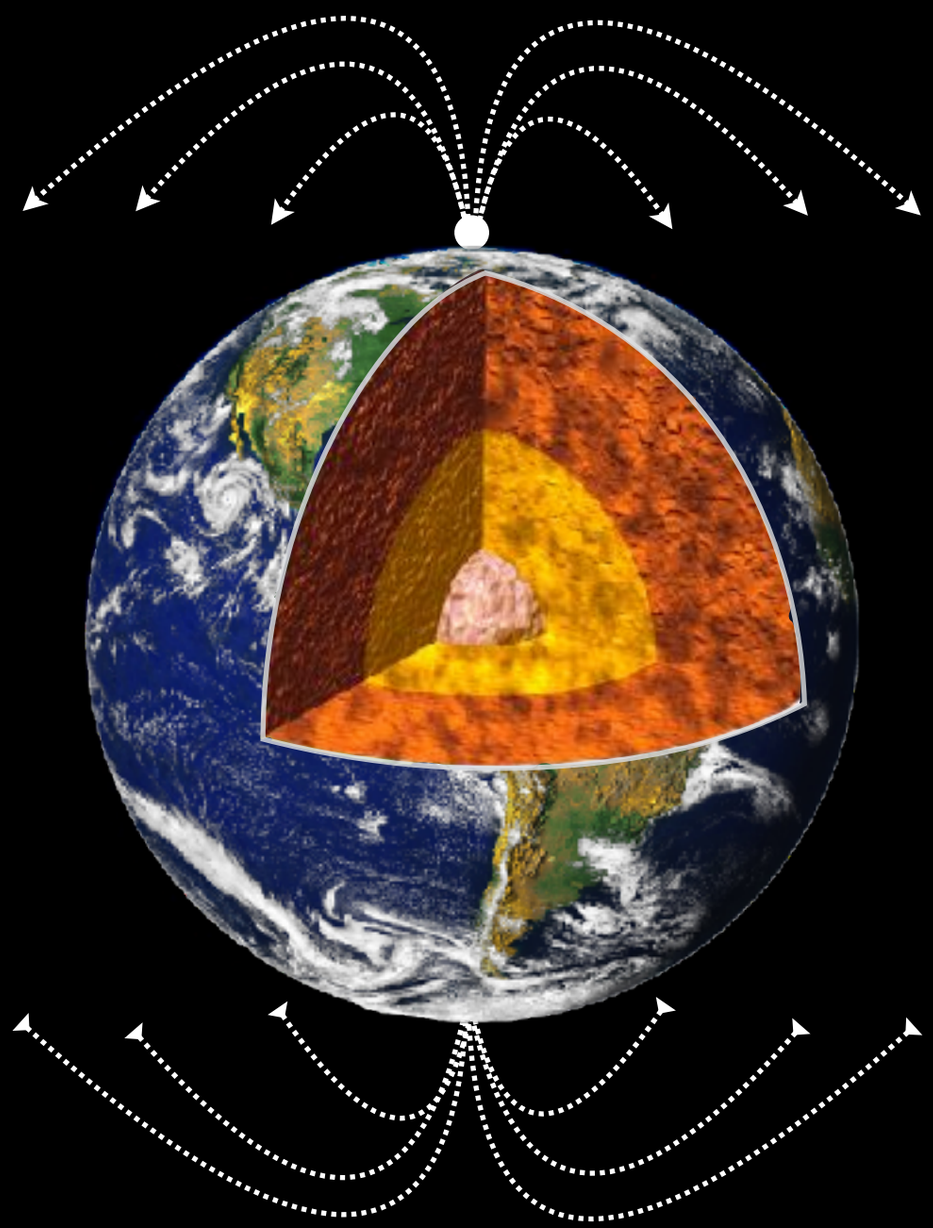
Impact of η(T,P) on the magnetic field

- *Heat transport*
- *Magnetic field*



Magnetic field: a look inside the outer core

- *Heat transport*
- *Magnetic field*



Magnetic field: a look inside the outer core

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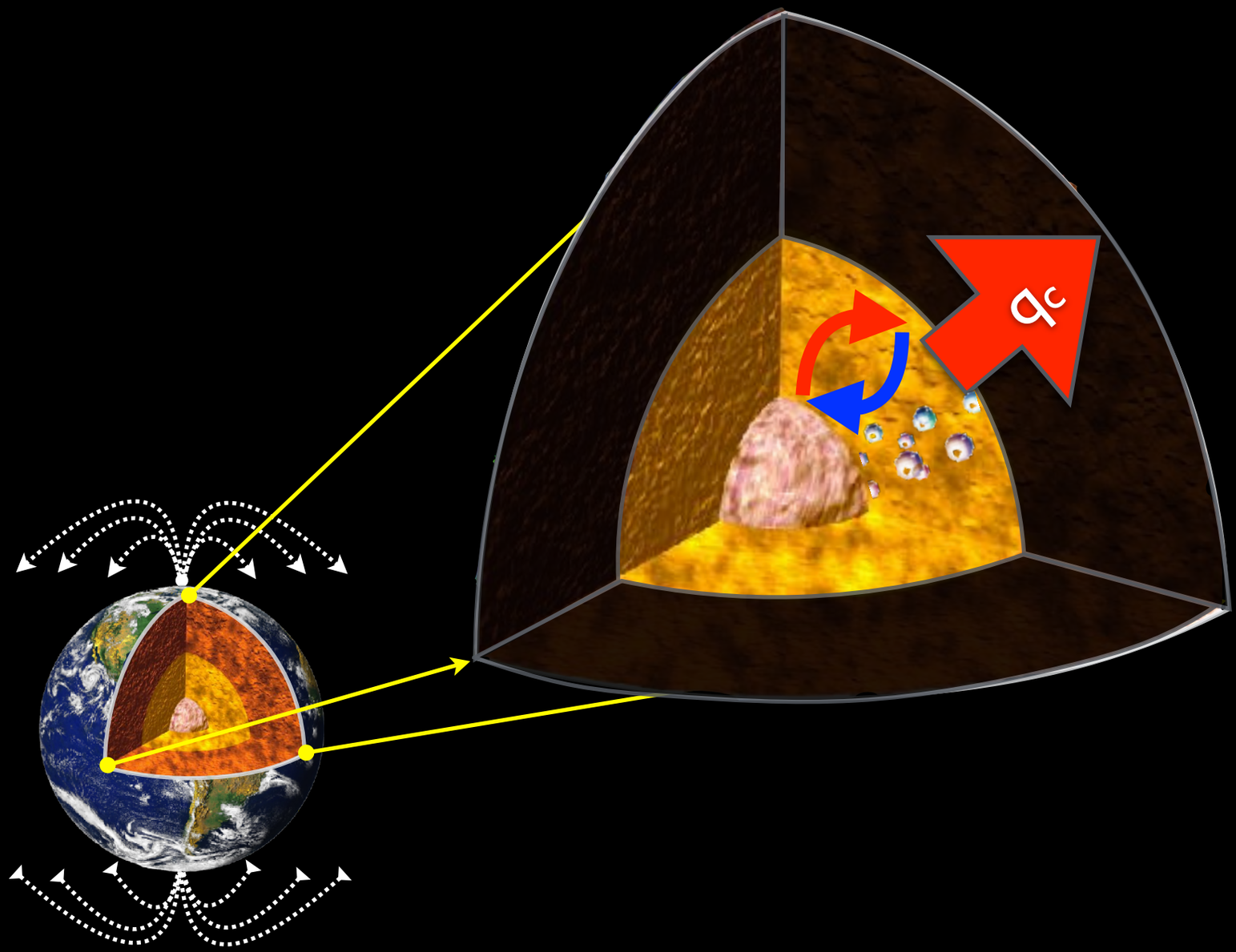
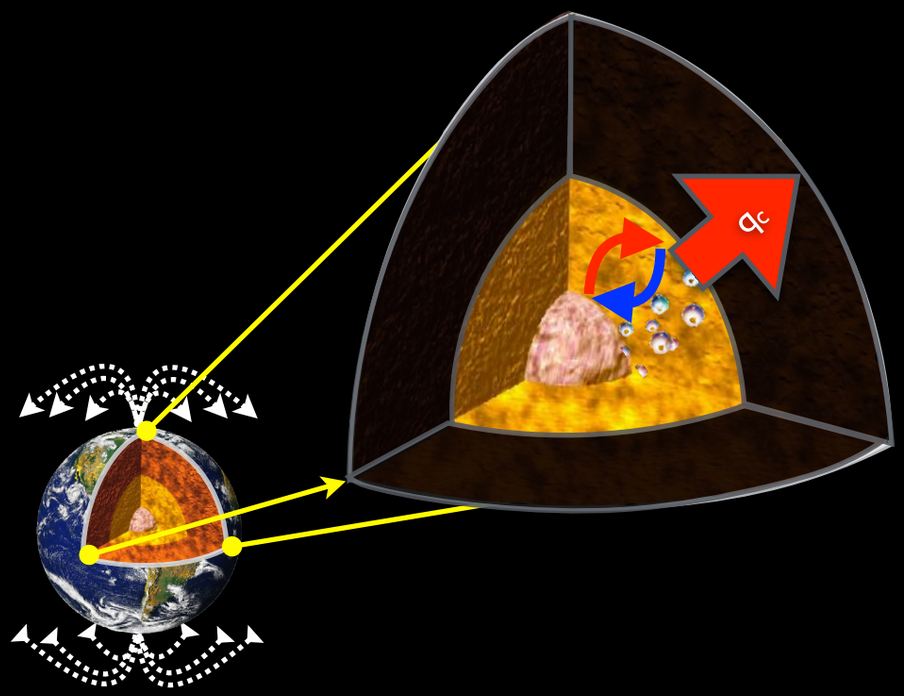
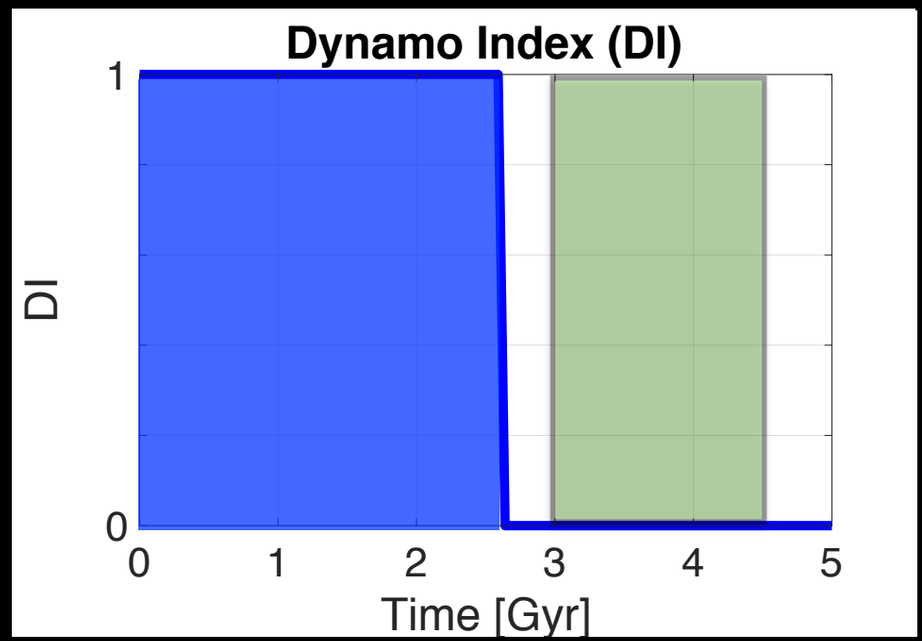


Earth's magnetic field: A "classic" paradox?

- *Heat transport*
- *Magnetic field*
- *Continuous dynamo*

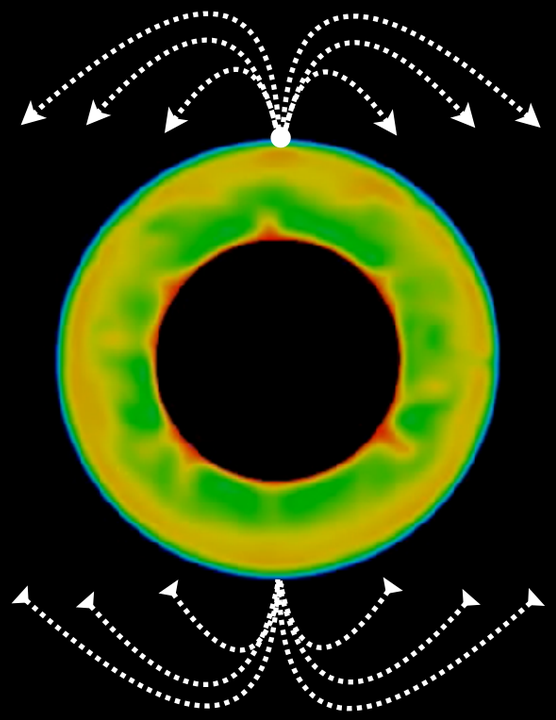




Stamenković + (2018, in prep)

Heat transport & magnetic field

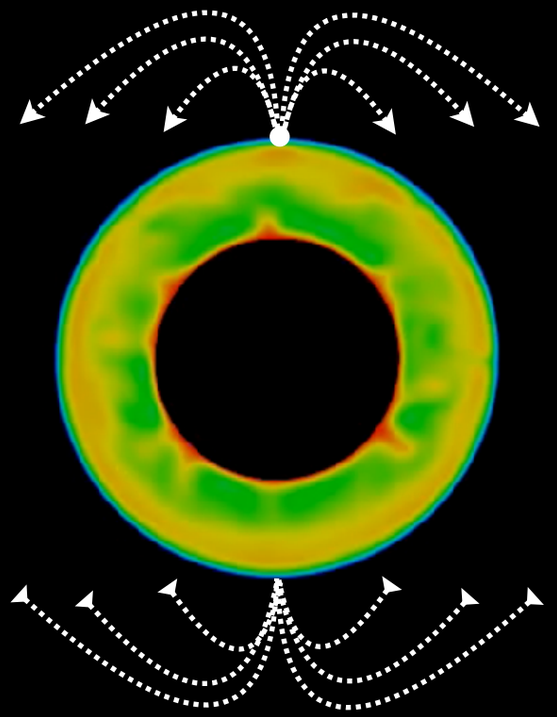
- *Heat transport*
- *Magnetic field*



Heat transport & magnetic field

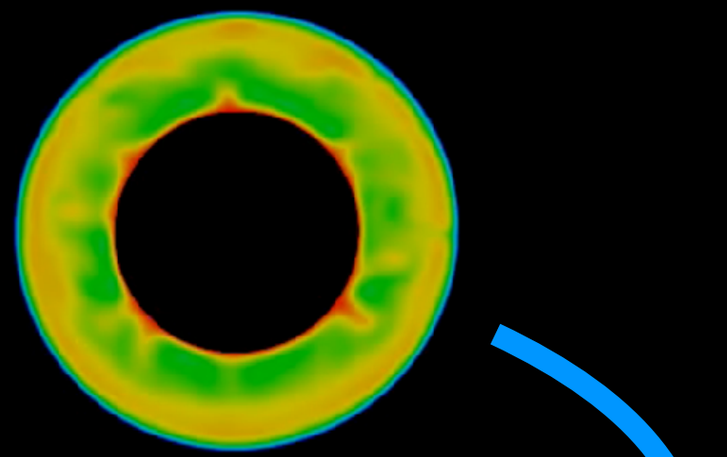
- *Heat transport*
- *Magnetic field*

- *We can satisfy constraints*
- *Longer melt (few Gyr)*
- *More sluggish lower mantle convection*
- *Continuous dynamo*



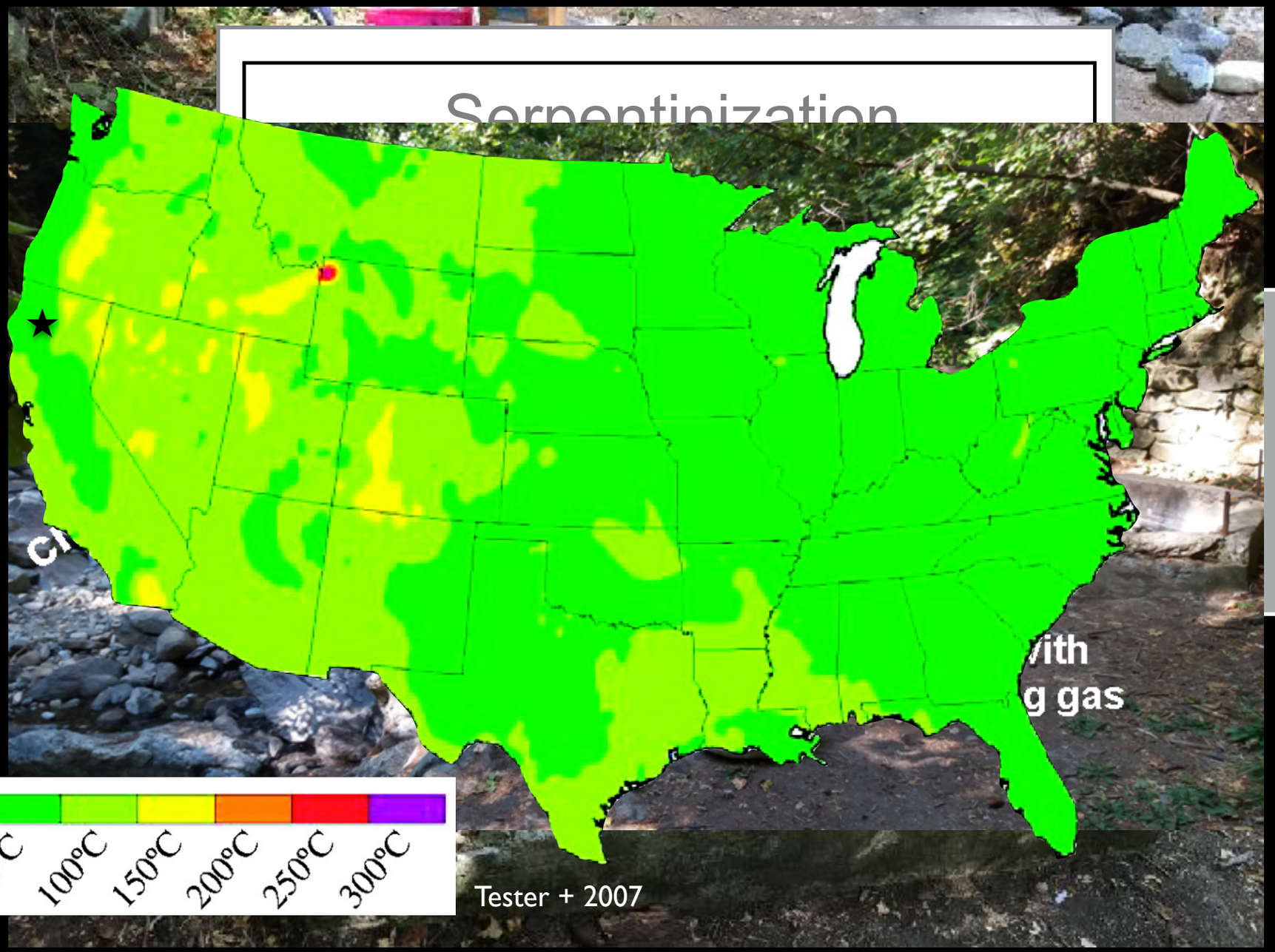
Geophysical H_2 generation

- *Heat transport*
- *Magnetic field*
- *Redox (r): H_2*



Geophysical H_2 generation: From field to model

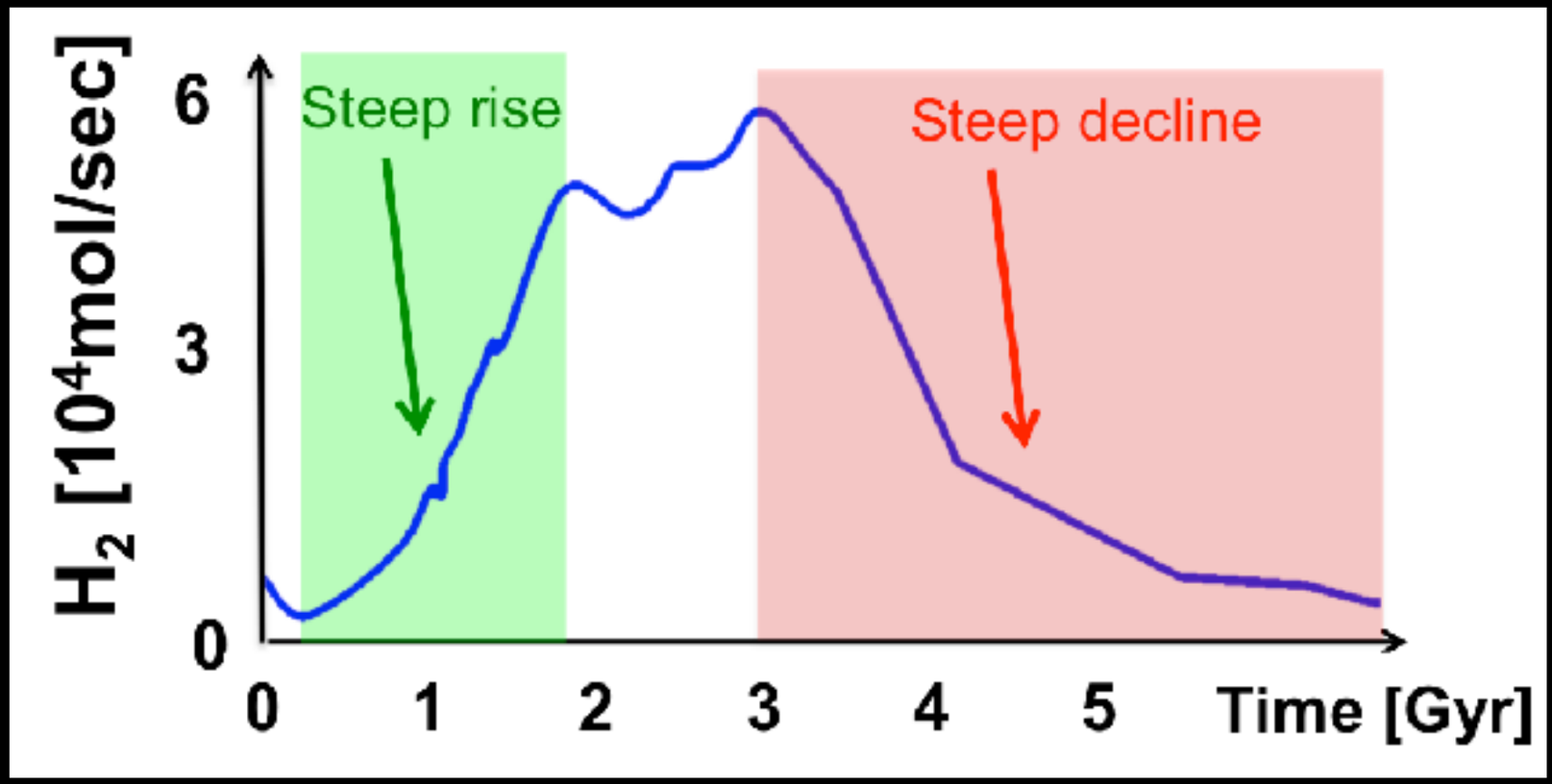
- *Heat transport*
- *Magnetic field*
- *Redox (r): H_2*



Stamenković (2015)

H_2: Time variability on Earth

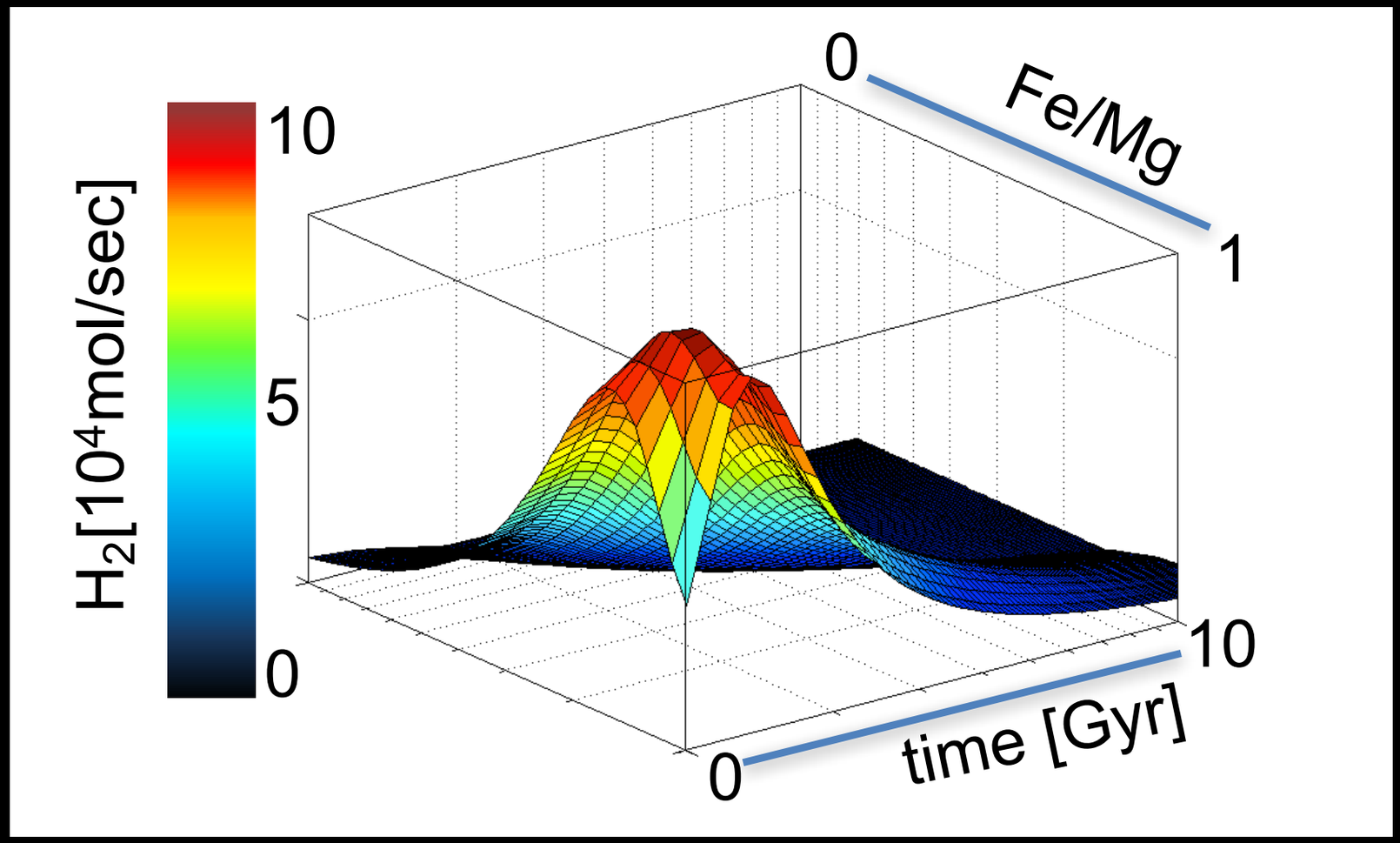
- *Heat transport*
- *Magnetic field*
- *Redox (r): H_2*



Stamenković (2015); Stamenković + (20178 in prep)

H_2: Function of Fe/Mg

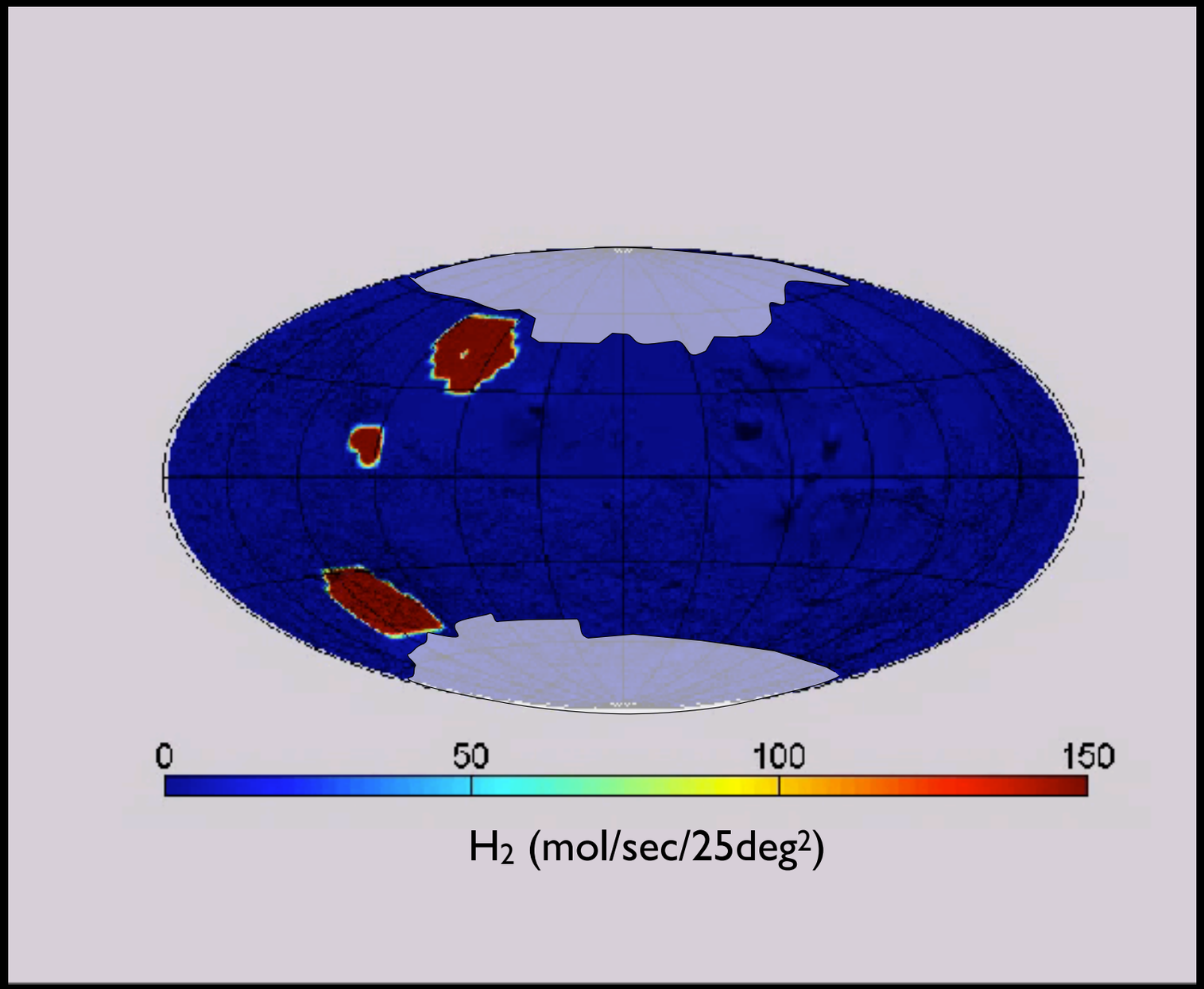
- *Heat transport*
- *Magnetic field*
- *Redox (r): H_2*



Stamenković (2015); Stamenković + (2018, in prep)

H_2: Testing our Earth model on Mars with TGO

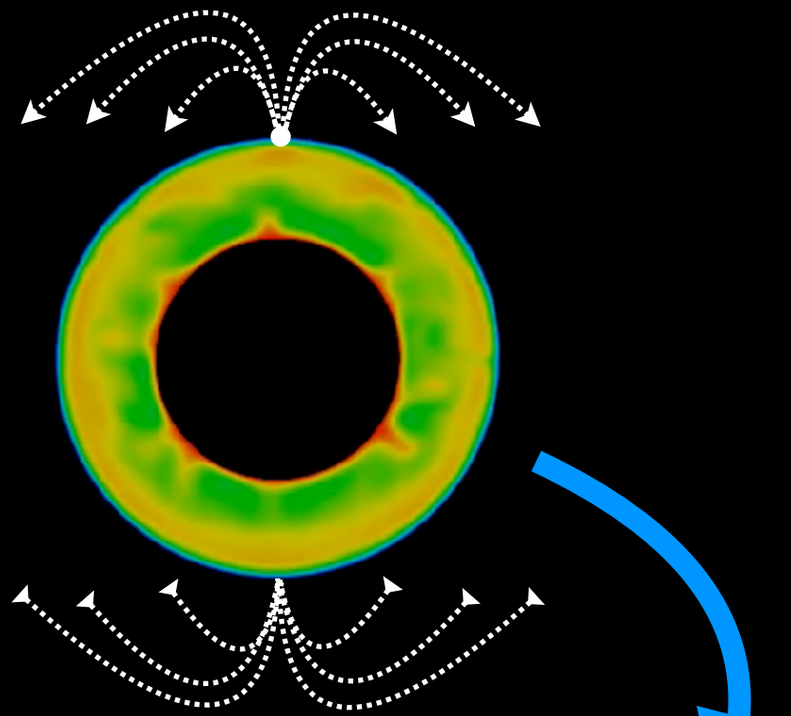
- *Heat transport*
- *Magnetic field*
- *Redox (r): H_2*

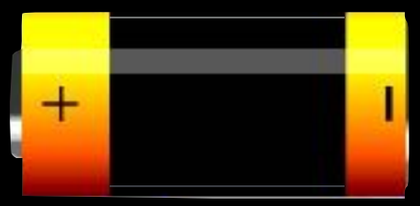


Stamenković (2015); Stamenković + (2018, in prep)

Geophysical H_2 generation

- *Heat transport*
- *Magnetic field*
- *Redox (r): H_2*

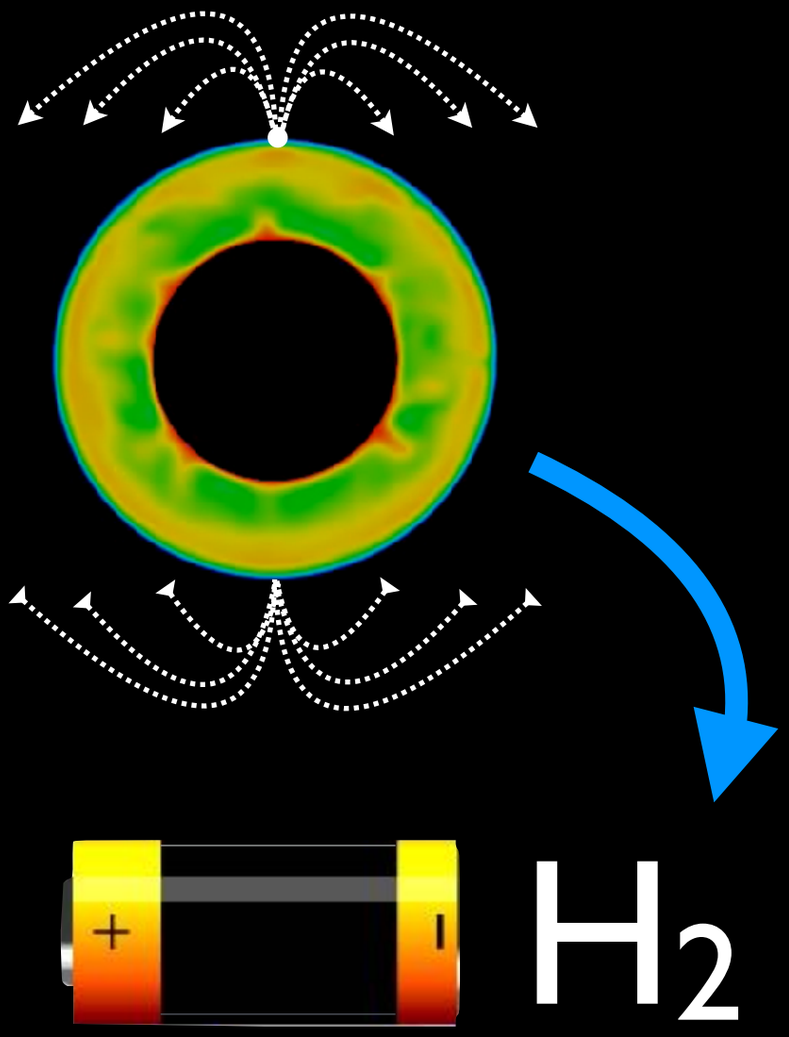




H_2

Geophysical H_2 generation

- *Heat transport*
- *Magnetic field*
- *Redox (r): H_2*
  - *Strongly time-dependent*
  - *Peak after ~1-2 Gyr*
  - *Very low today*
  - *Mars = testbed*



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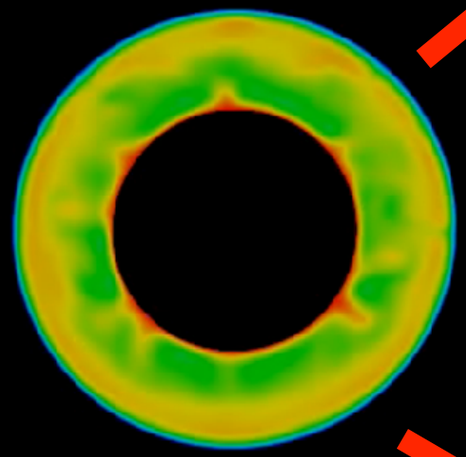
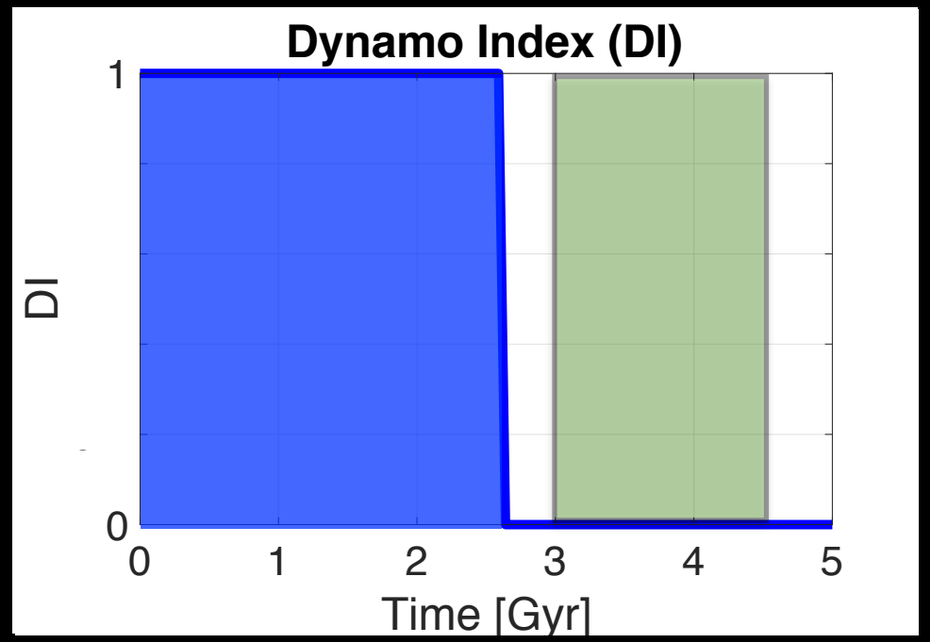
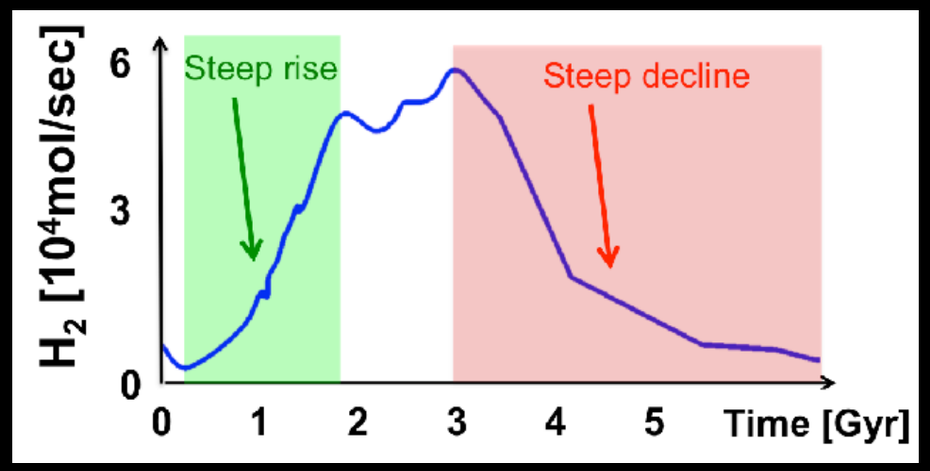
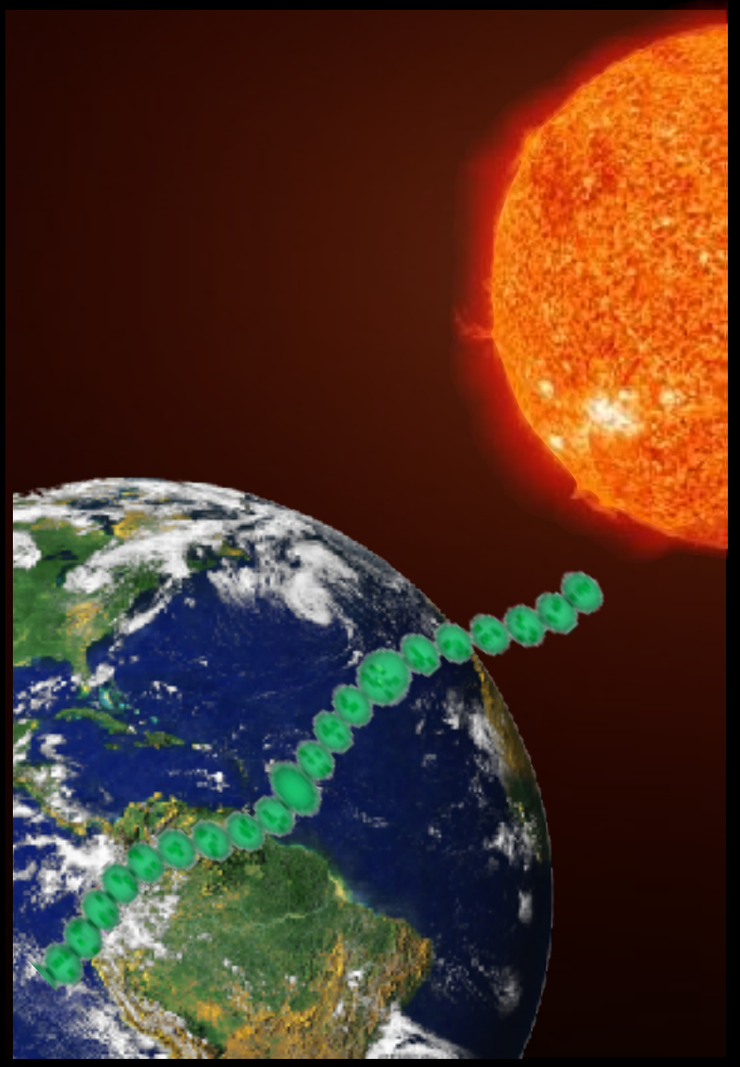






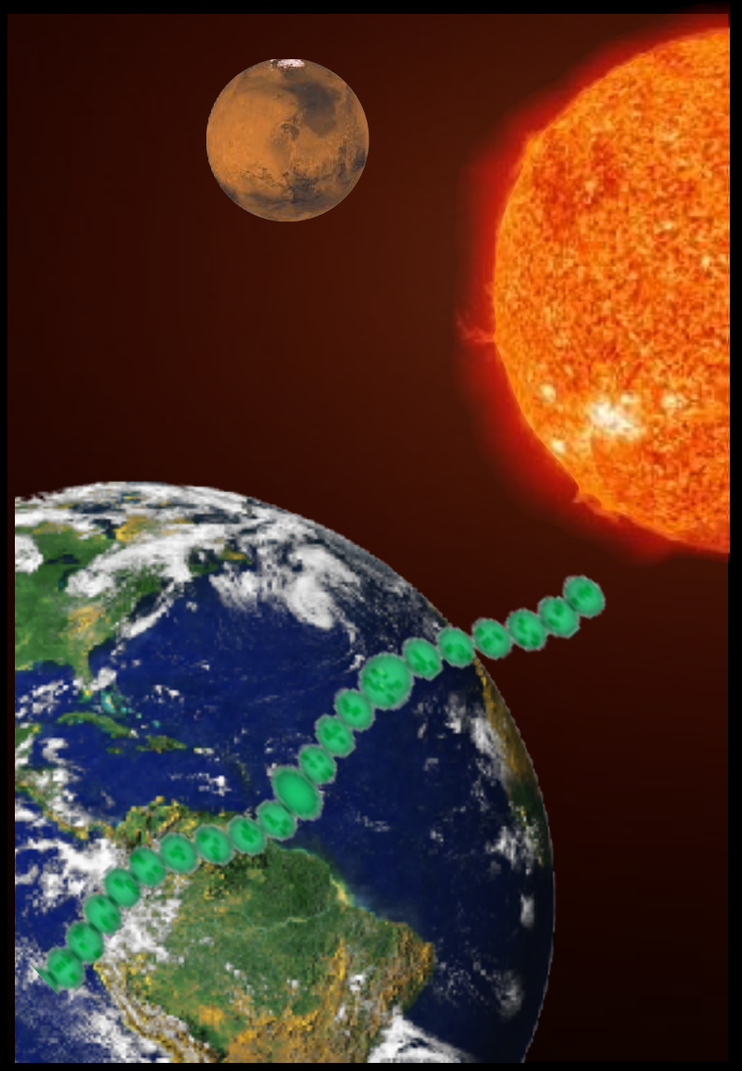
DATA: From Earth

- Paleothermometers (*Evolution*).
- Paleomagnetic record (*Dynamo*).
- Seismology (*Rheology, Dynamics*).
- Modern Hydrogen/Methane generation via serpentinization, radiolysis, and Fischer-Tropsch type reactions - deep versus shallow processes.
  - Aqua de Ney (*CA*),
  - The Cedars (*CA*),
  - Zlatibor (*SERBIA*), and many more.



DATA: From Earth to Mars

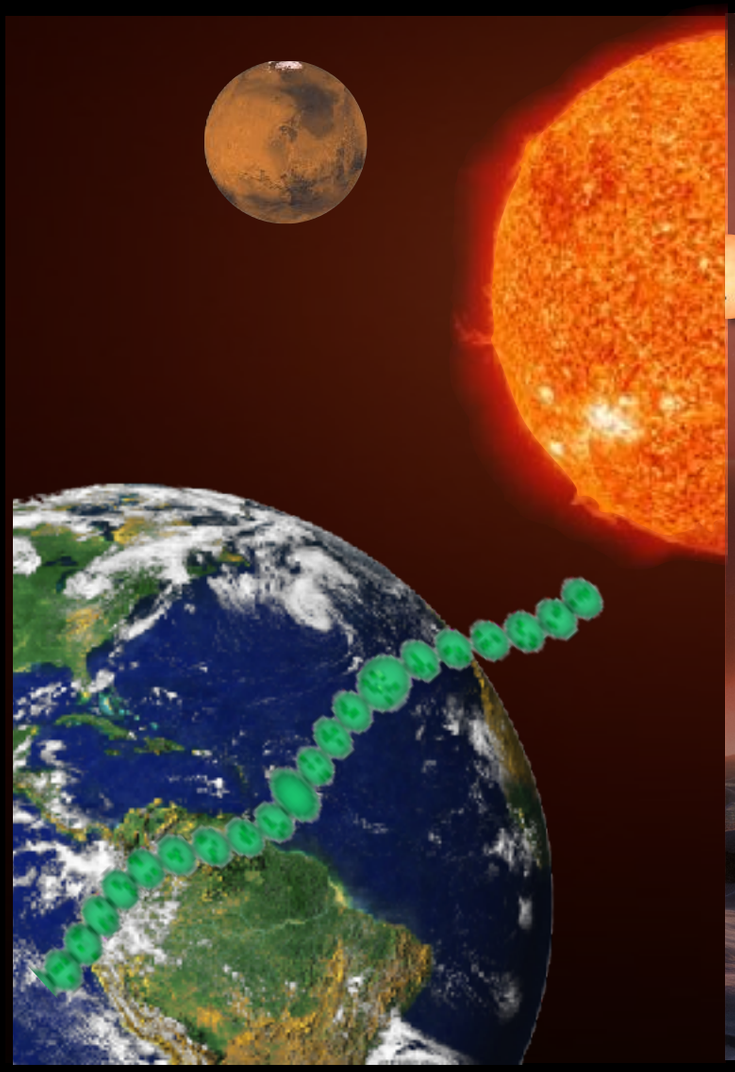
- Methane and hydrogen maps with ExoMars TGO (2017)?
- Local methane variation with MSL?
- Insight?
- Mars 2020?
- **Potential missions beyond 2020?**



DATA: From Earth to Mars to TRAPPIST-1

The TRAPPIST-1 planets are our chance to constrain global geophysics on Earth!

- Close & spectroscopically characterisable transiting planets.
- Earth-size but variable composition/ structure/insolation.
- Spectroscopy with HST to infer atmospheric composition & volcanic activity (O_2, H_2, S, Mg, Ca,…).
- Io-Jupiter-like dynamo interaction to infer dynamo with LOFAR.
- We are getting ready for JWST!

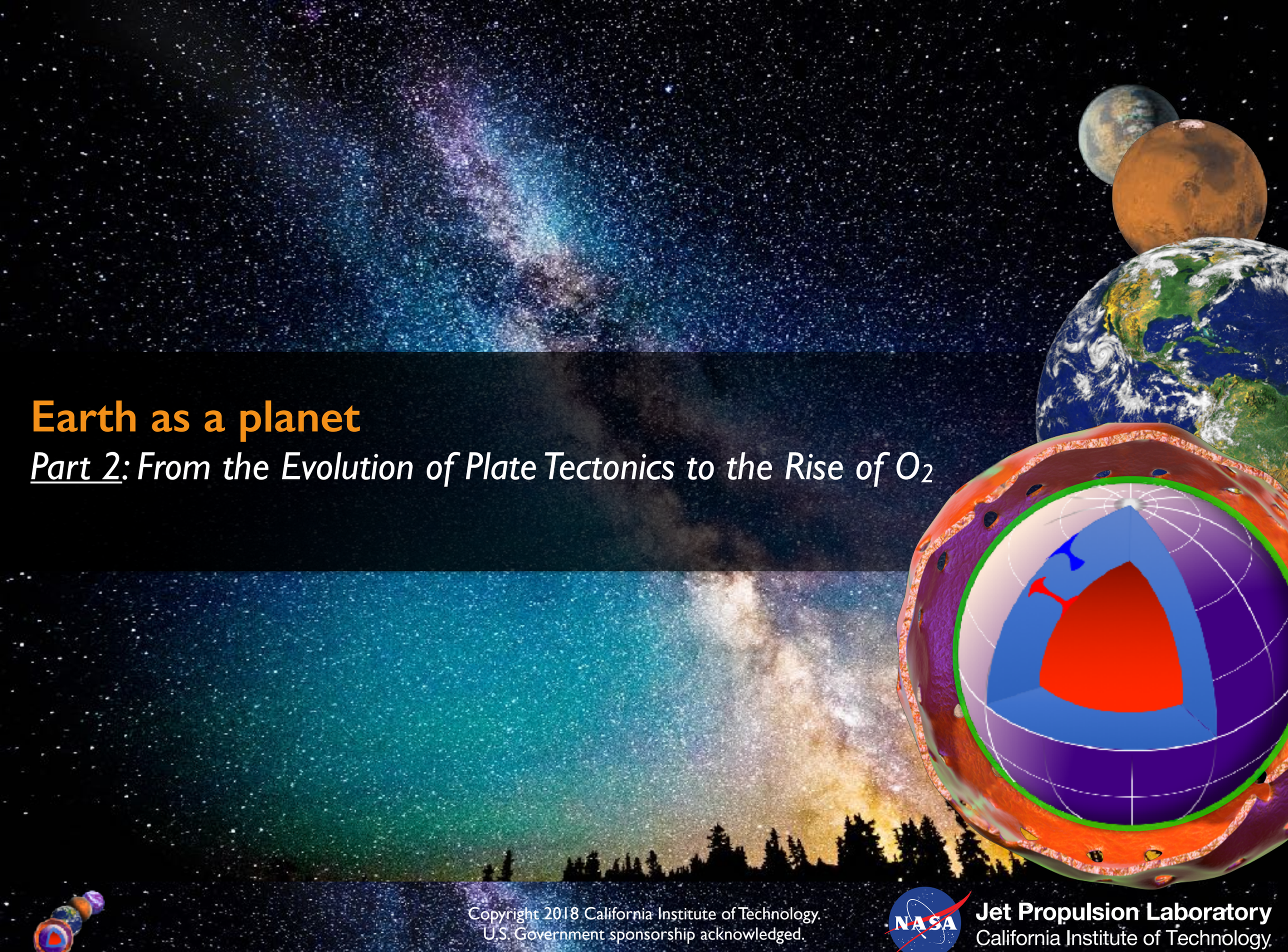


Conclusions

- Mantle viscosity is strongly pressure-dependent.
  - *The evolution of the Earth strongly depends on initial conditions and a probabilistic thermal evolution approach is needed.*
  - *Longer lifetime for dynamos and melting on Earth.*
  - *More sluggish lower mantle convection.*
- Time- and spatially fluctuating H_2 production predictable for the Earth. H_2 formation by serpentinization starts only after ~1-2 Gyr, strongly dependent of Fe/Mg ratio and mineralogy.
- We need to focus on Earth but we must simultaneously include the diversity of planets to unveil the fundamental principles at work on Earth.
  - *Mars helps us constrain the fundamental processes at work, which we could not do on Earth alone - ExoMars TGO, MSL, and MarsX.*
  - *The TRAPPIST-1 system allows us to explore "many Earths".*

Earth as a planet

Part 2: From the Evolution of Plate Tectonics to the Rise of O_2



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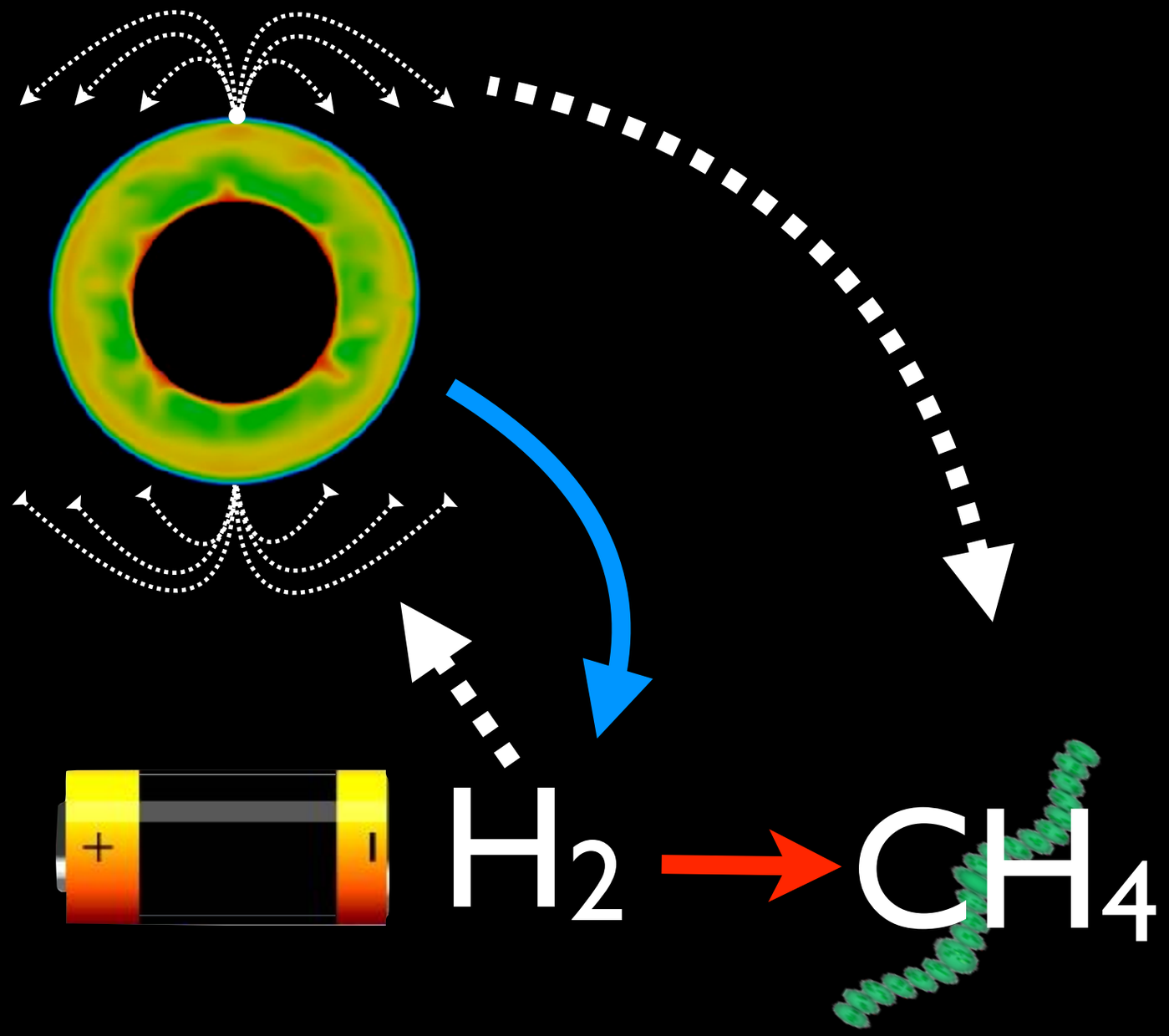
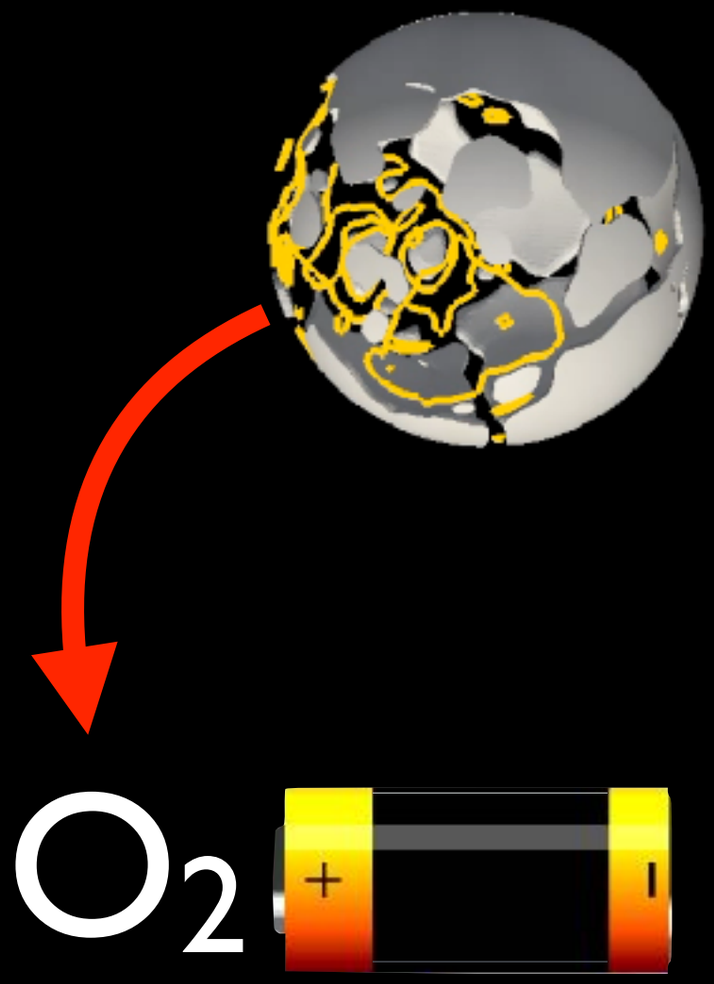


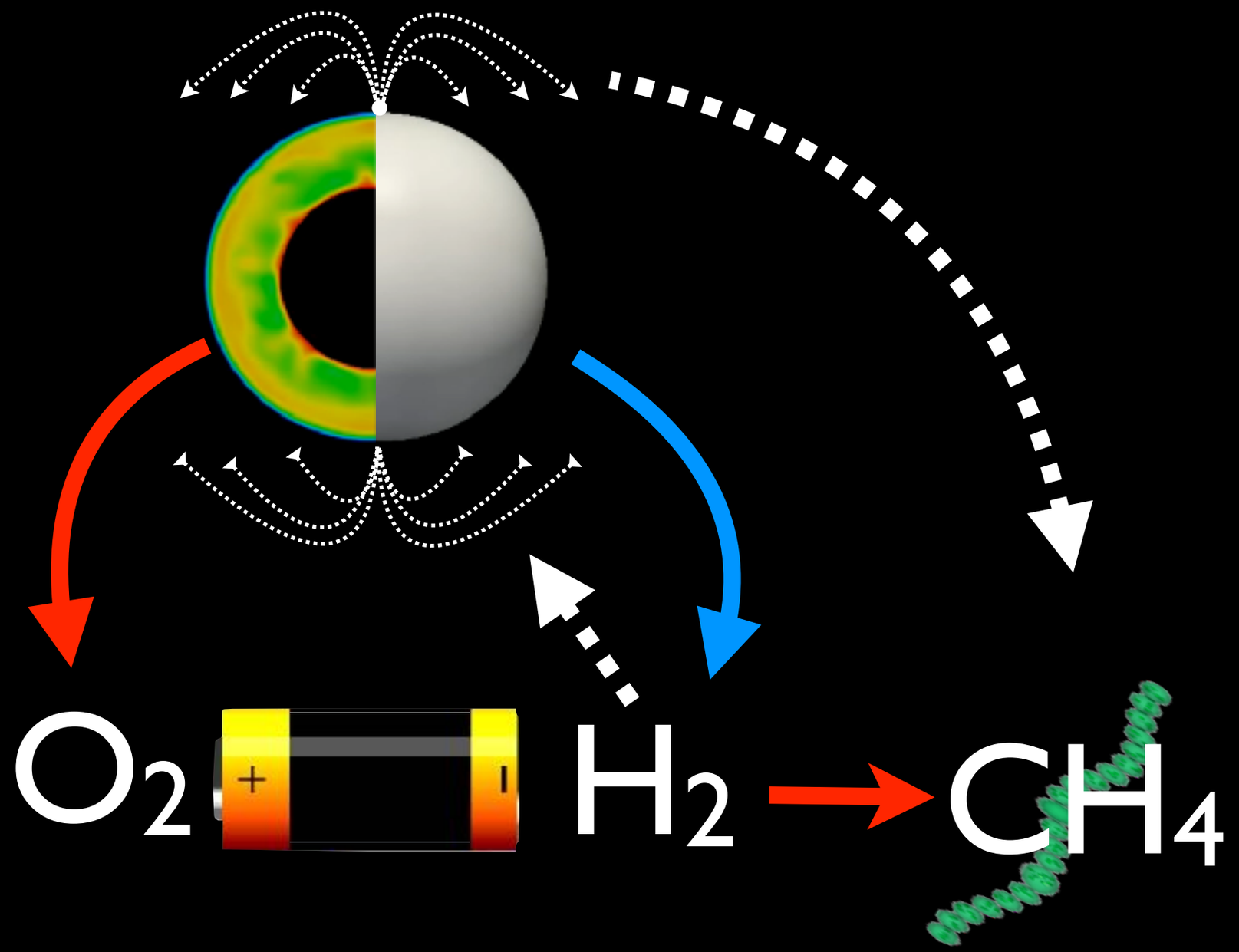
Part 2: Plate tectonics & O_2

- *Tectonic mode*
- *Redox (o): O_2*



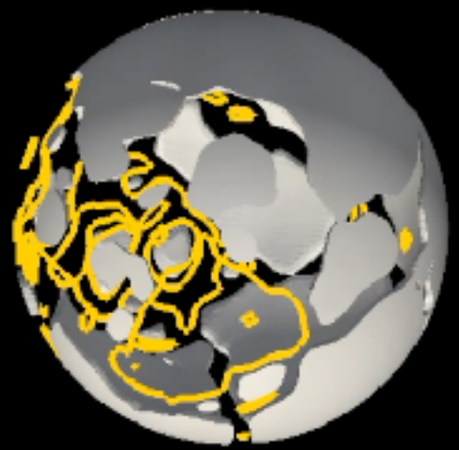
A greater picture: Global geophysics & life

- *Heat transport*
- *Tectonic mode*
- *Magnetic field*
- *Redox (r): H_2*
- *Redox (o): O_2*



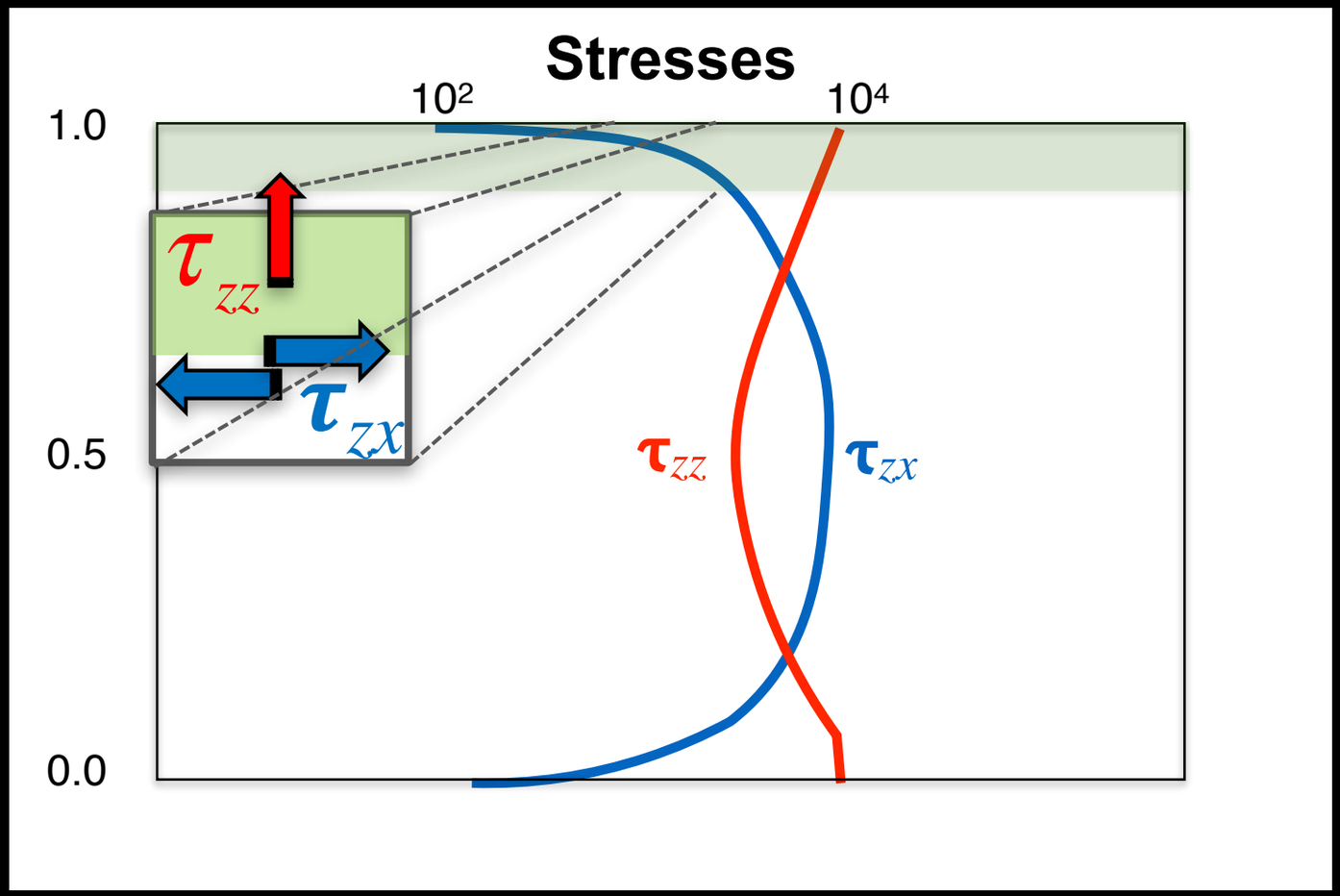
The evolution of plate tectonics

- *Tectonic mode*



Classic steady-state stresses

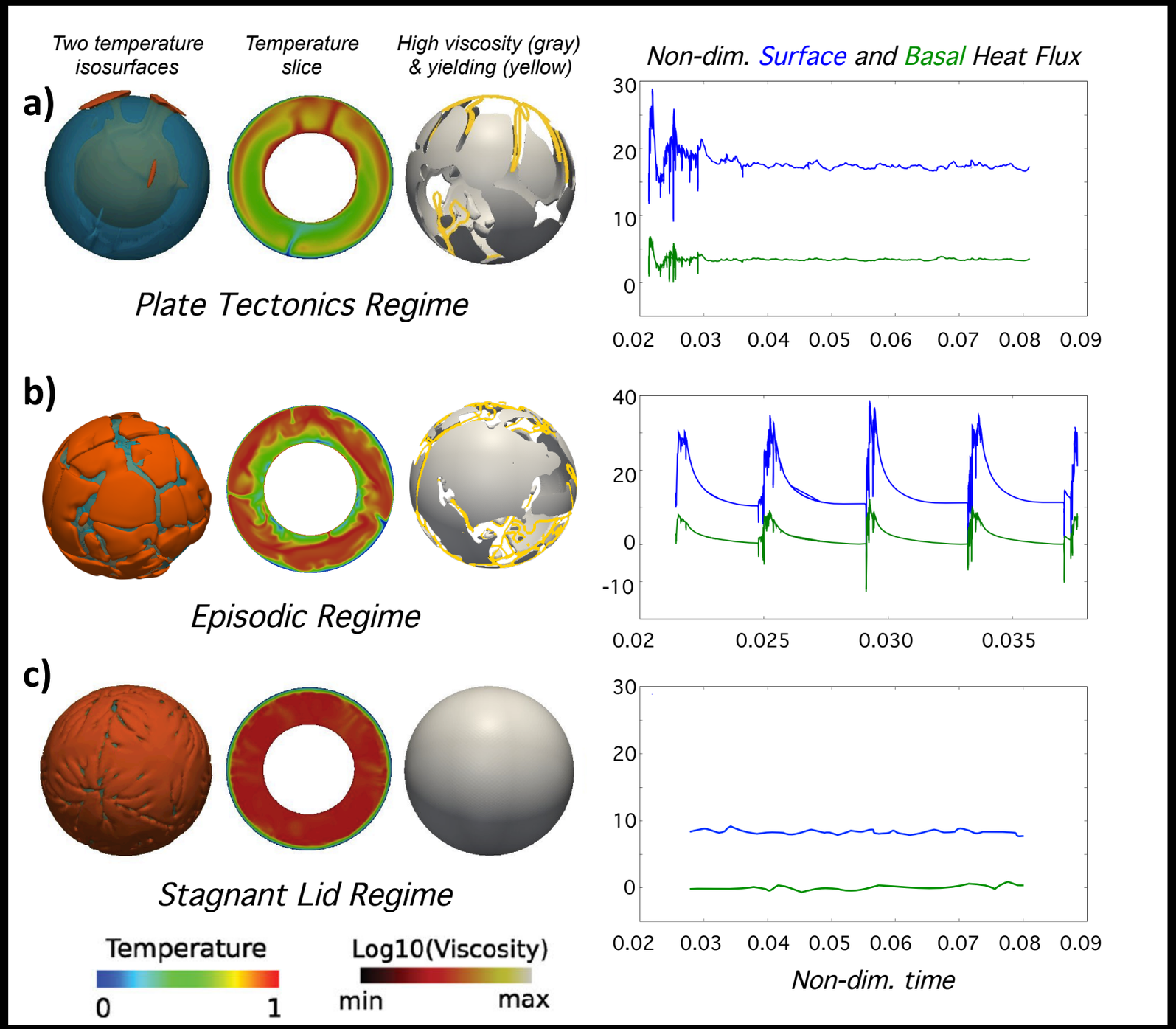
- *Tectonic mode*



Stamenković + (2016)

Different tectonic modes

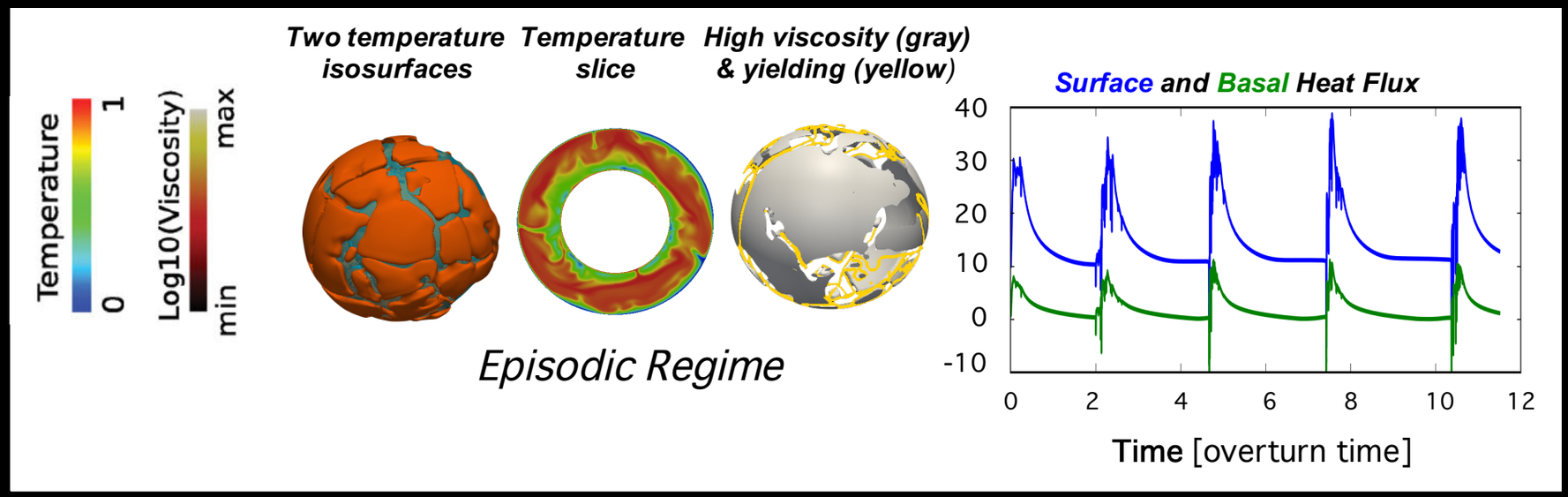
- *Tectonic mode*



Stamenković + (2016)

Away from thermal equilibrium

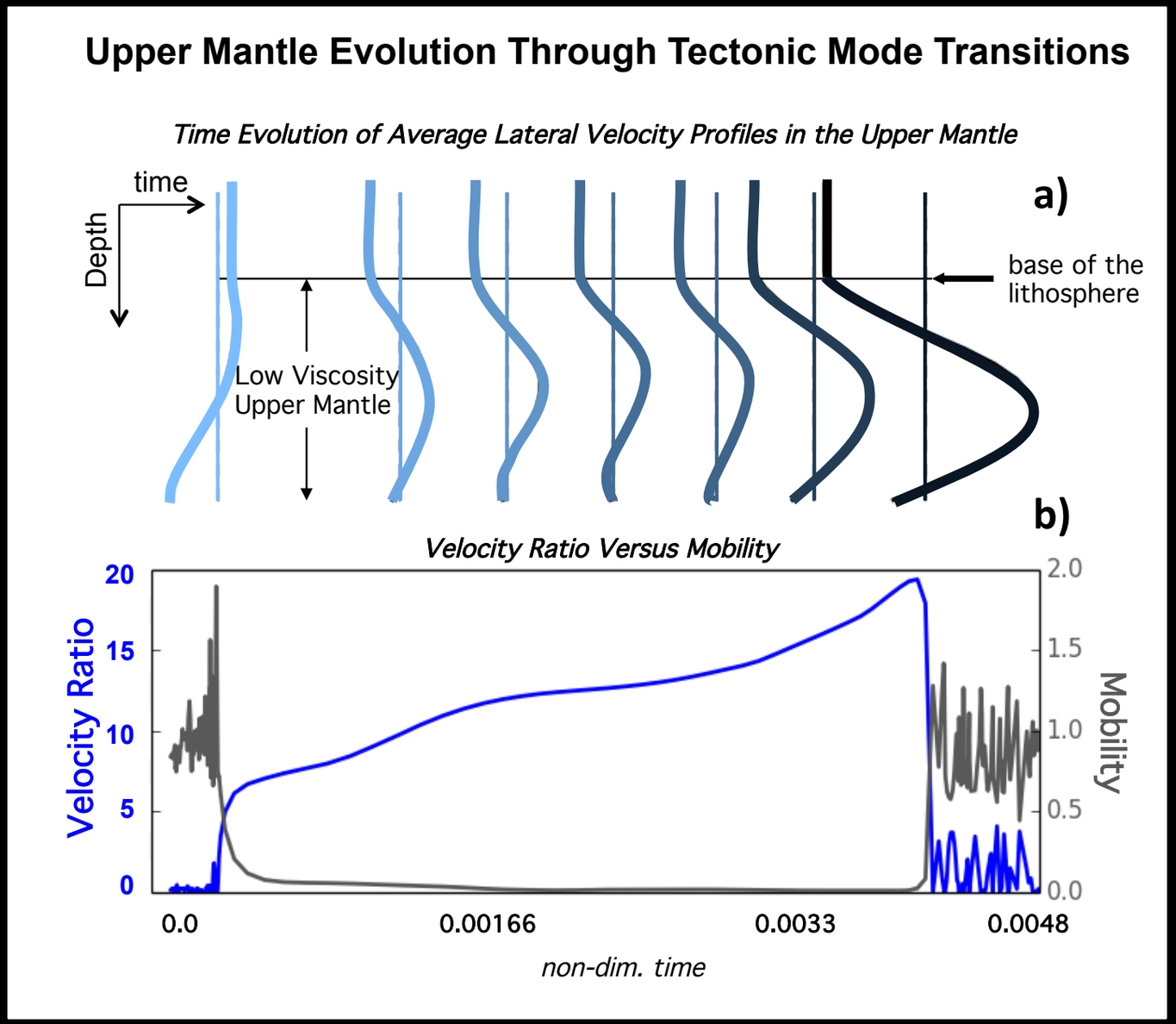
- *Tectonic mode*



Stamenković + (2016)

Away from thermal equilibrium

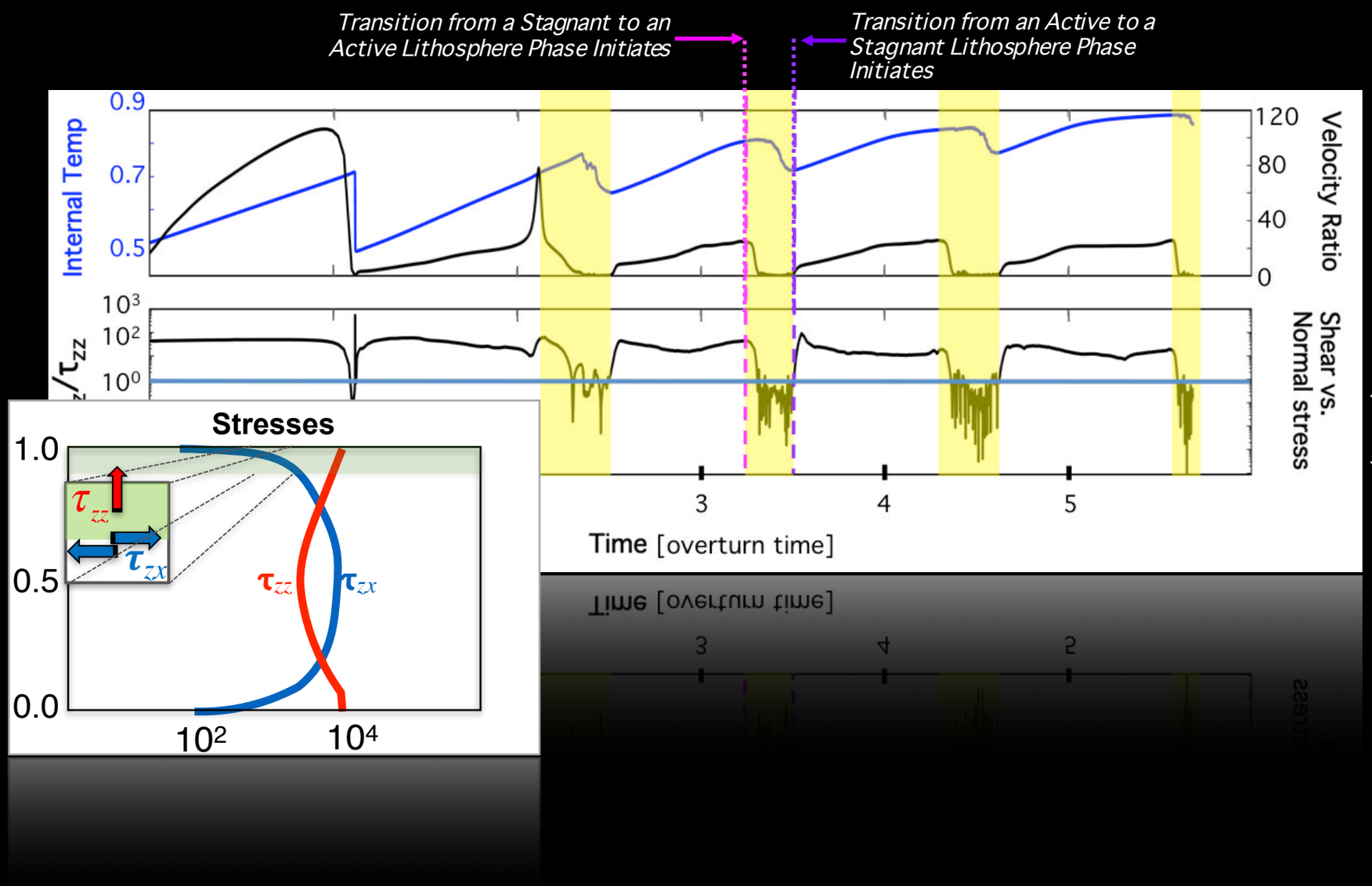
- *Tectonic mode*



Stamenković + (2016)

Away from thermal equilibrium

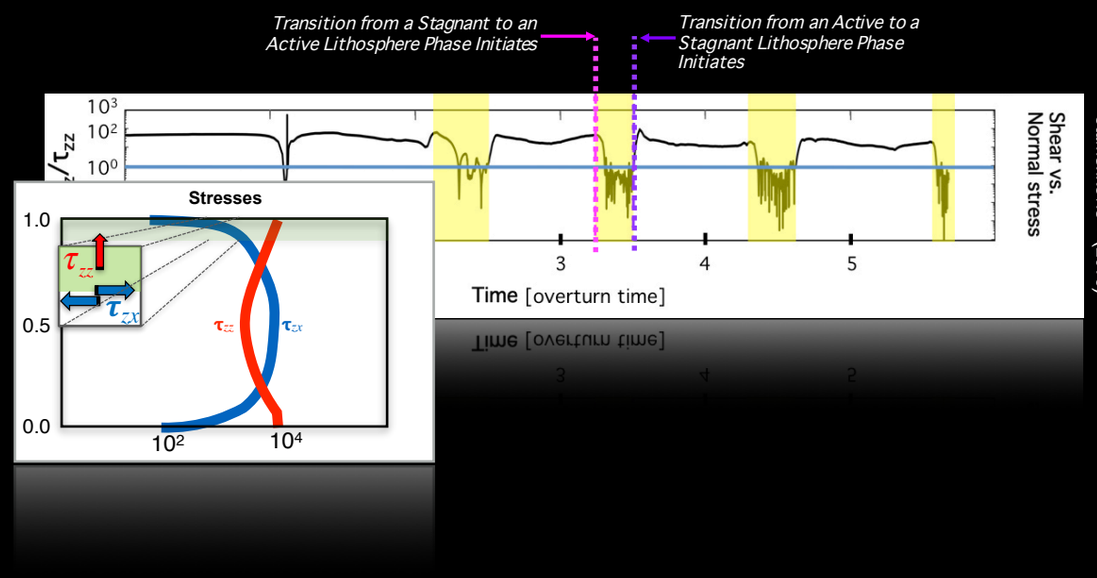
- *Tectonic mode*



Stamenković + (2016)

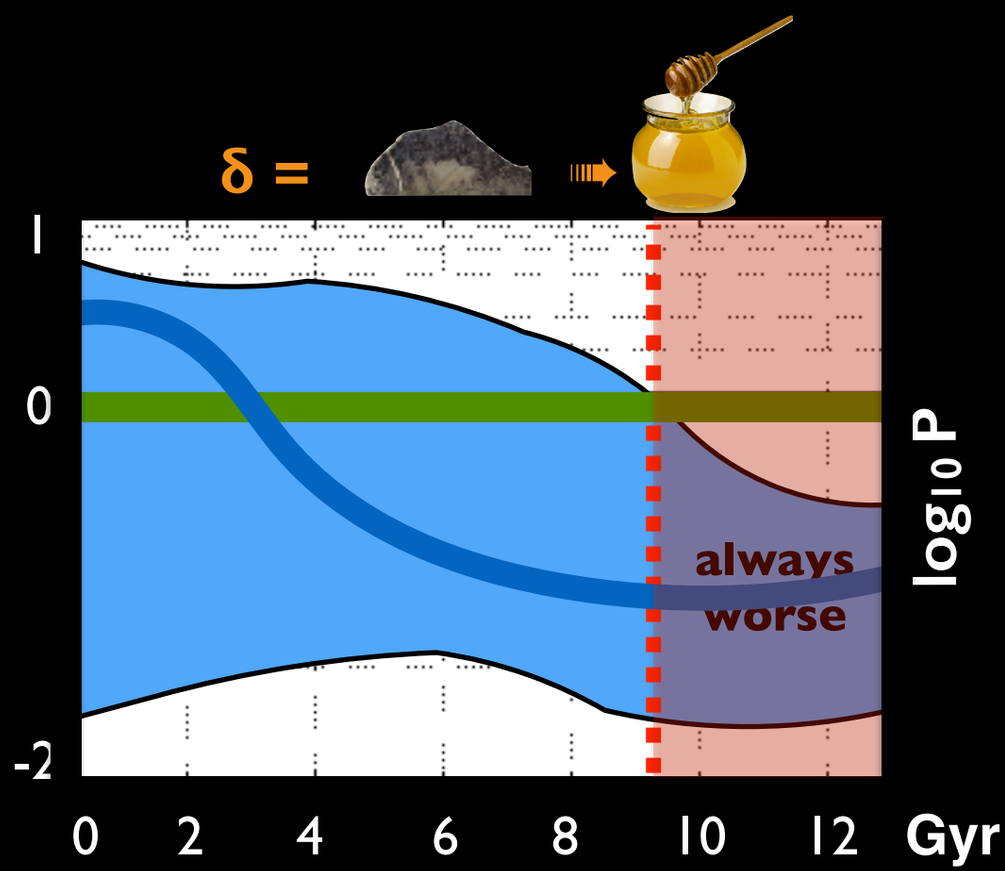
Away from thermal equilibrium

- *Tectonic mode*
  - *Plate tectonics becomes less efficient when planet is hotter.*
  - *This is opposite to the "classic" behavior!*
    - *How plate tectonics depends on planet properties (e.g., water, Fe/Mg, etc.) changes dramatically.*



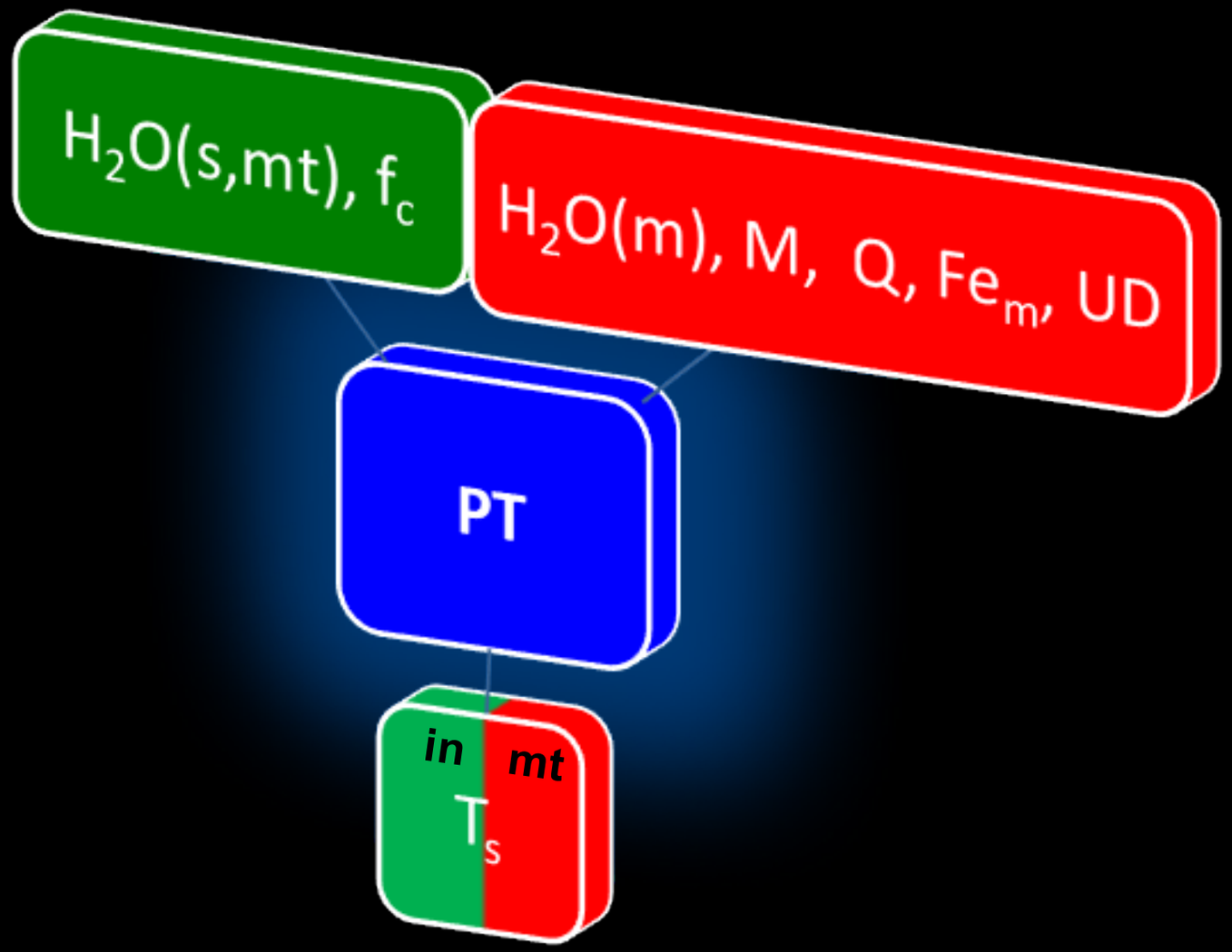
Method: "Good" or "Bad"

- *Tectonic mode*



Probabilistic approach

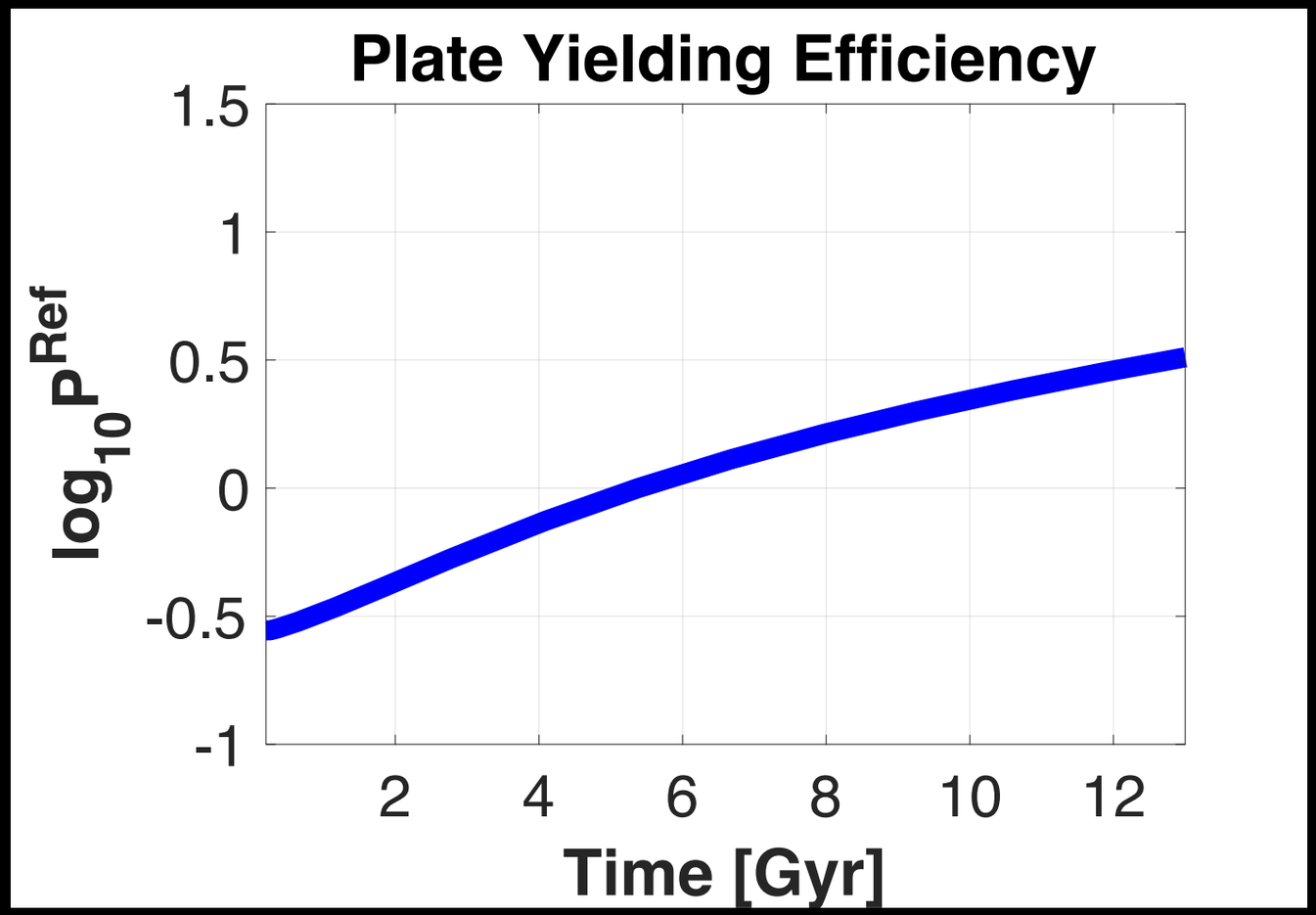
- *Tectonic mode*



Stamenković & Seager (2016), Stamenković (2018, in prep)

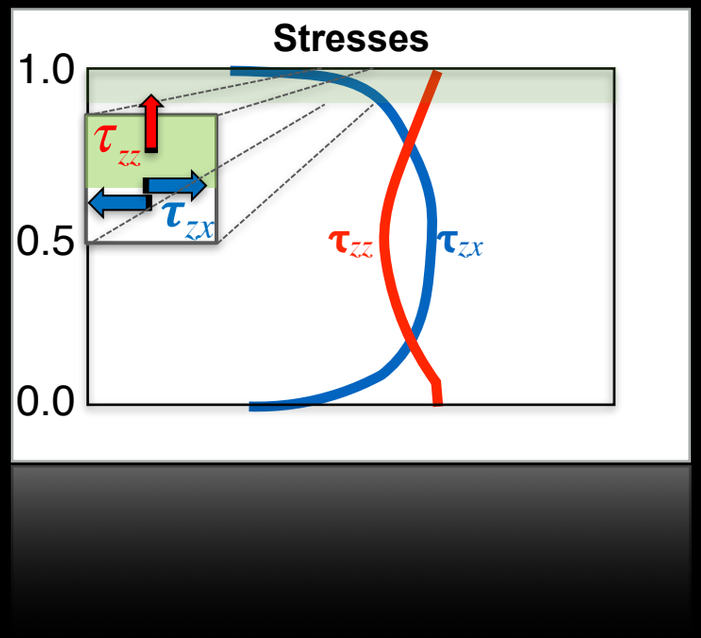
From hot plumes to cool maintenance?

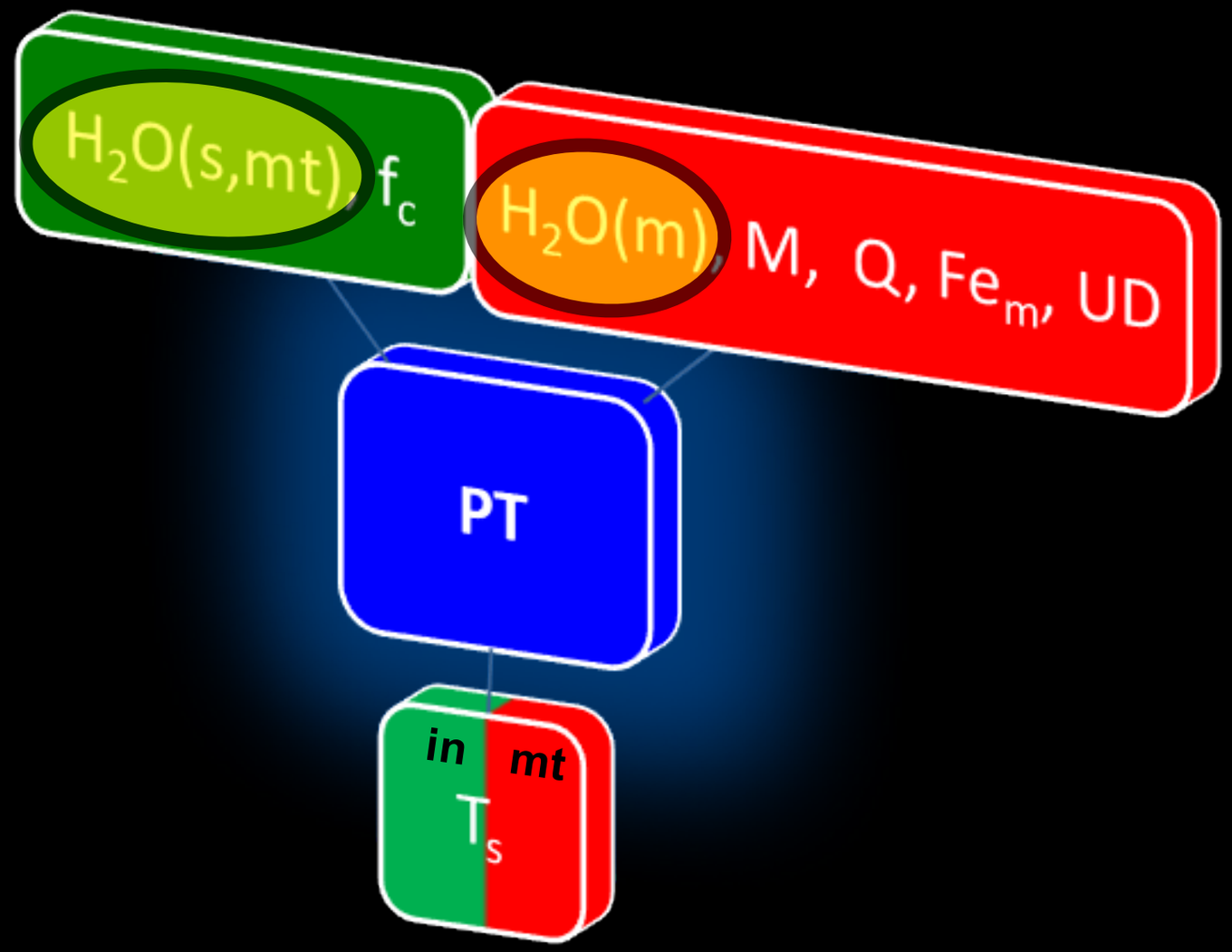
- *Tectonic mode*



Water distribution and plate tectonics

- *Tectonic mode*



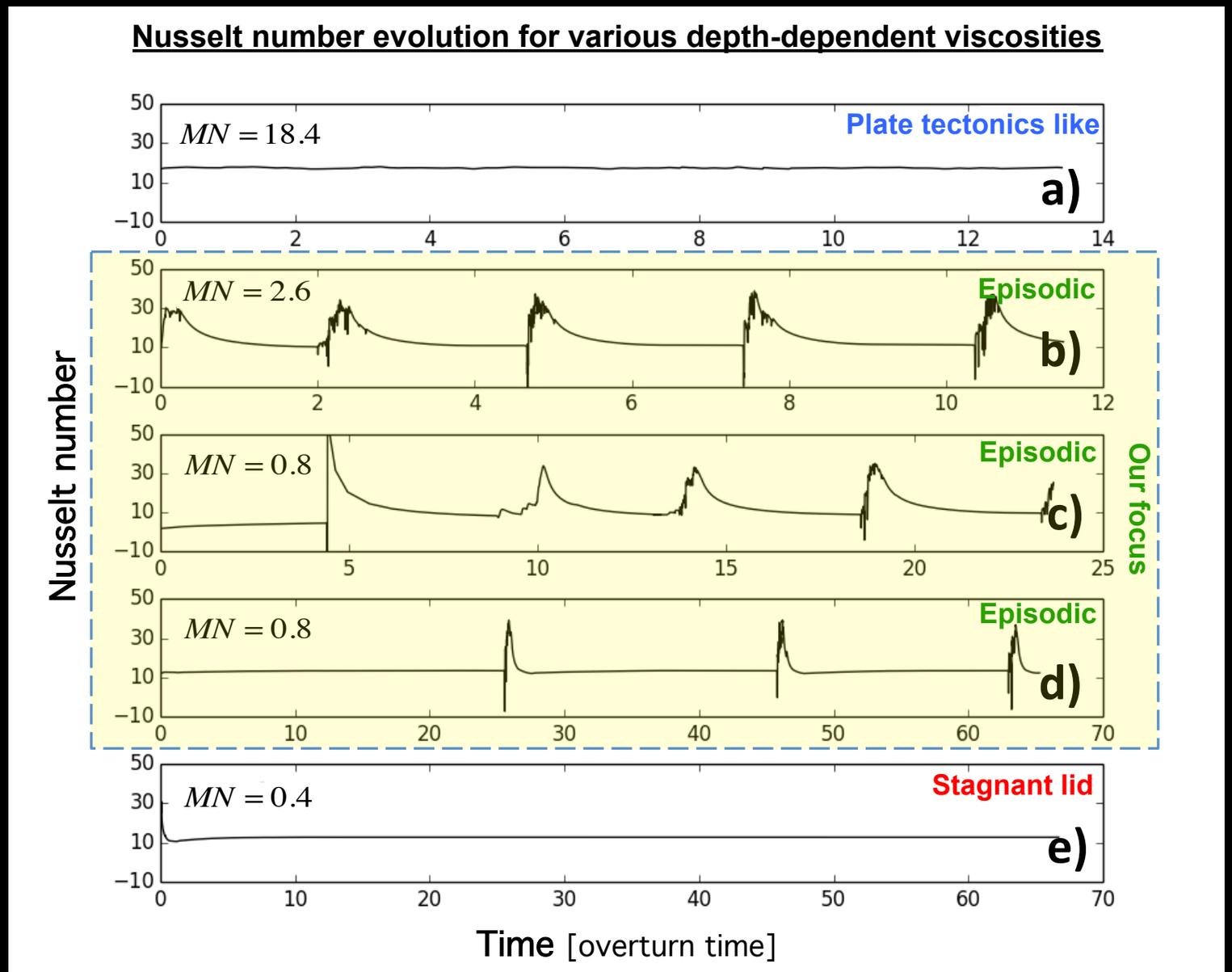


Stamenković & Seager (2016), Stamenković (2018, in prep)

Asthenospheric channels and plate tectonics

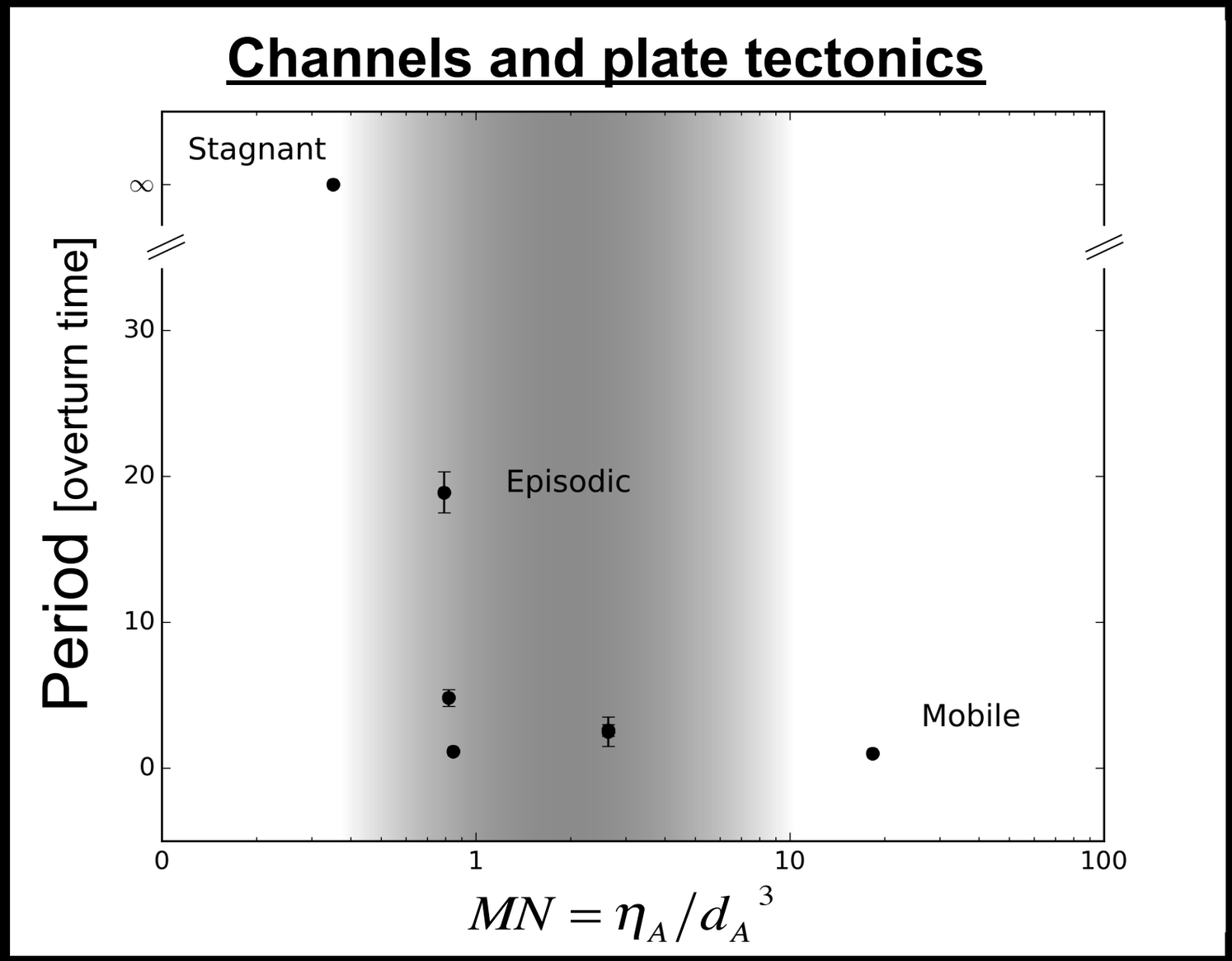
- *Tectonic mode*

$$MN = \eta_A / d_A^{\,3}$$



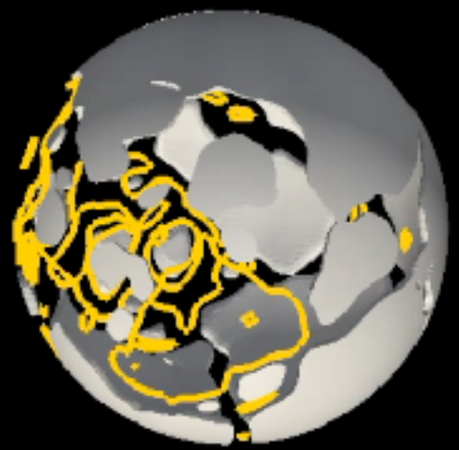
Asthenospheric channels and plate tectonics

- *Tectonic mode*



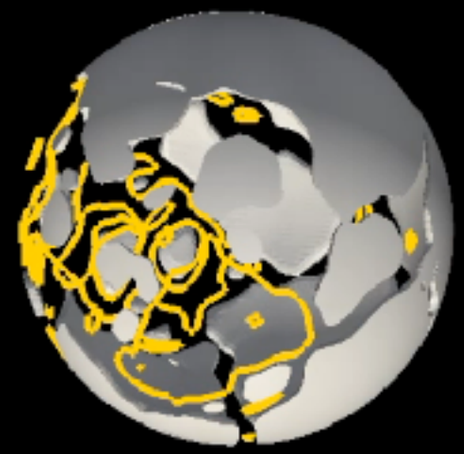
The evolution of plate tectonics

- *Tectonic mode*



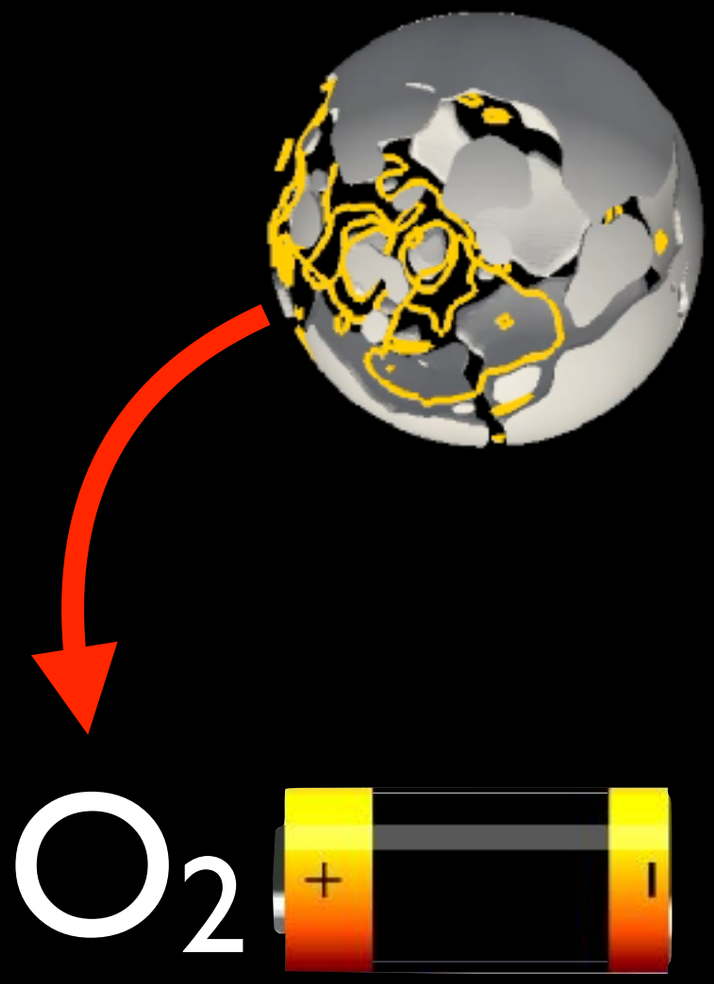
The evolution of plate tectonics

- *Tectonic mode*
  - *Non-equilibrium is critical*
  - *Bottom-up?*
  - *Early start*
  - *Maintenance self-regulating*
  - *Wet on top, dry inside otherwise flop*
  - *Asthenospheric channels as drivers*



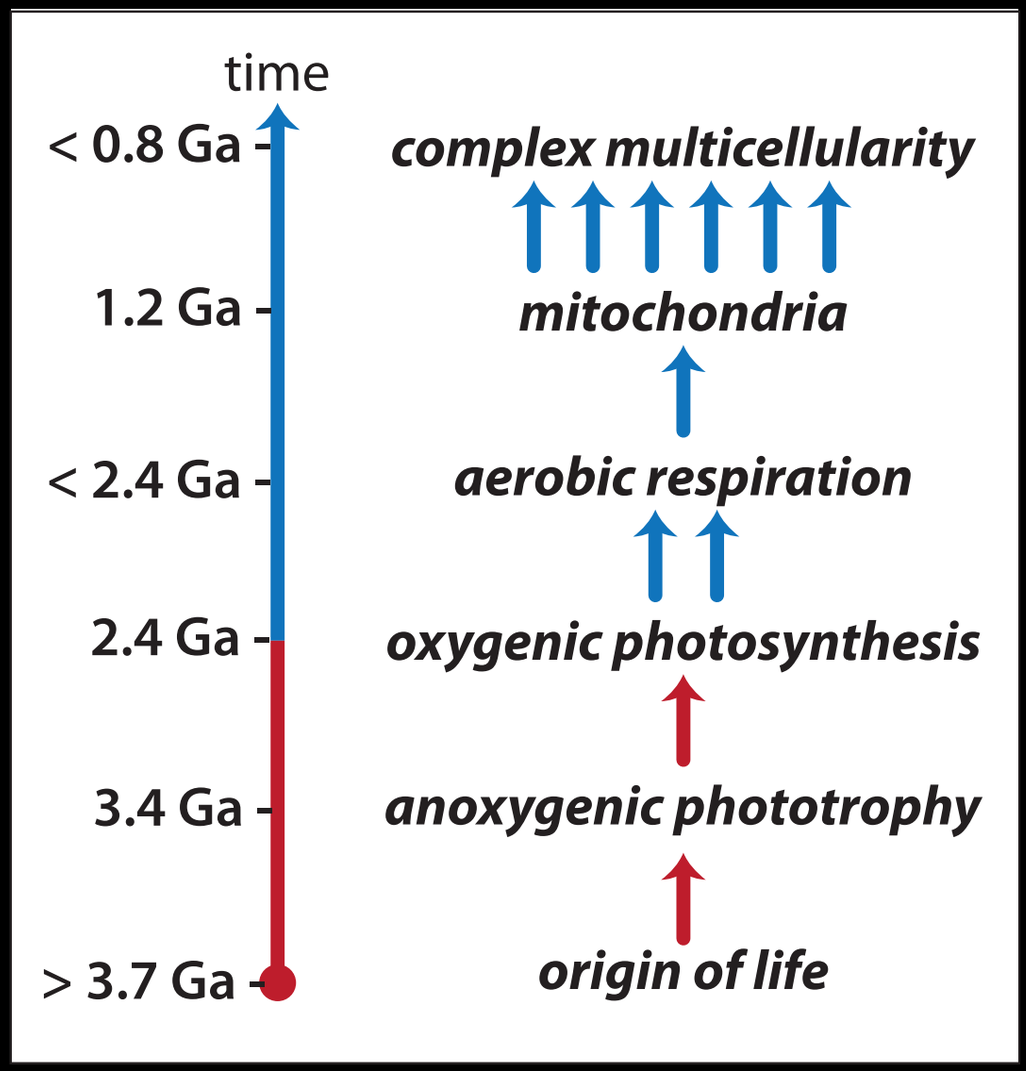
Towards oxygen

- *Tectonic mode*
- *Redox (o): O_2*



Towards the rise of oxygen

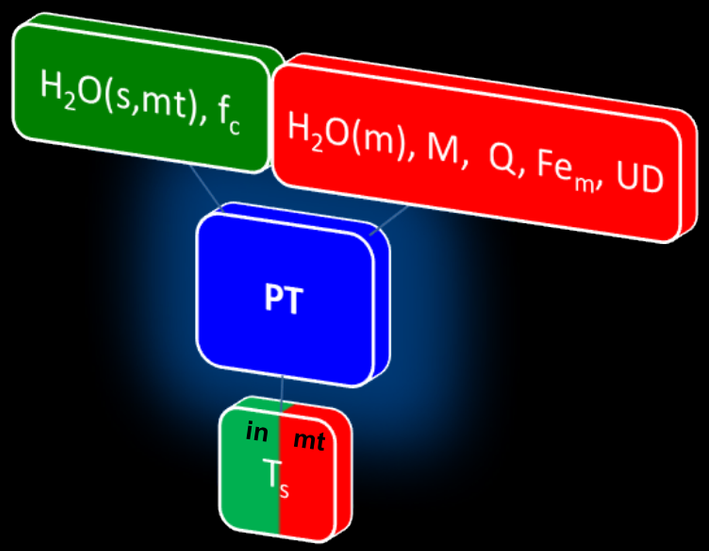
- *Tectonic mode*
- *Redox (o): O_2*



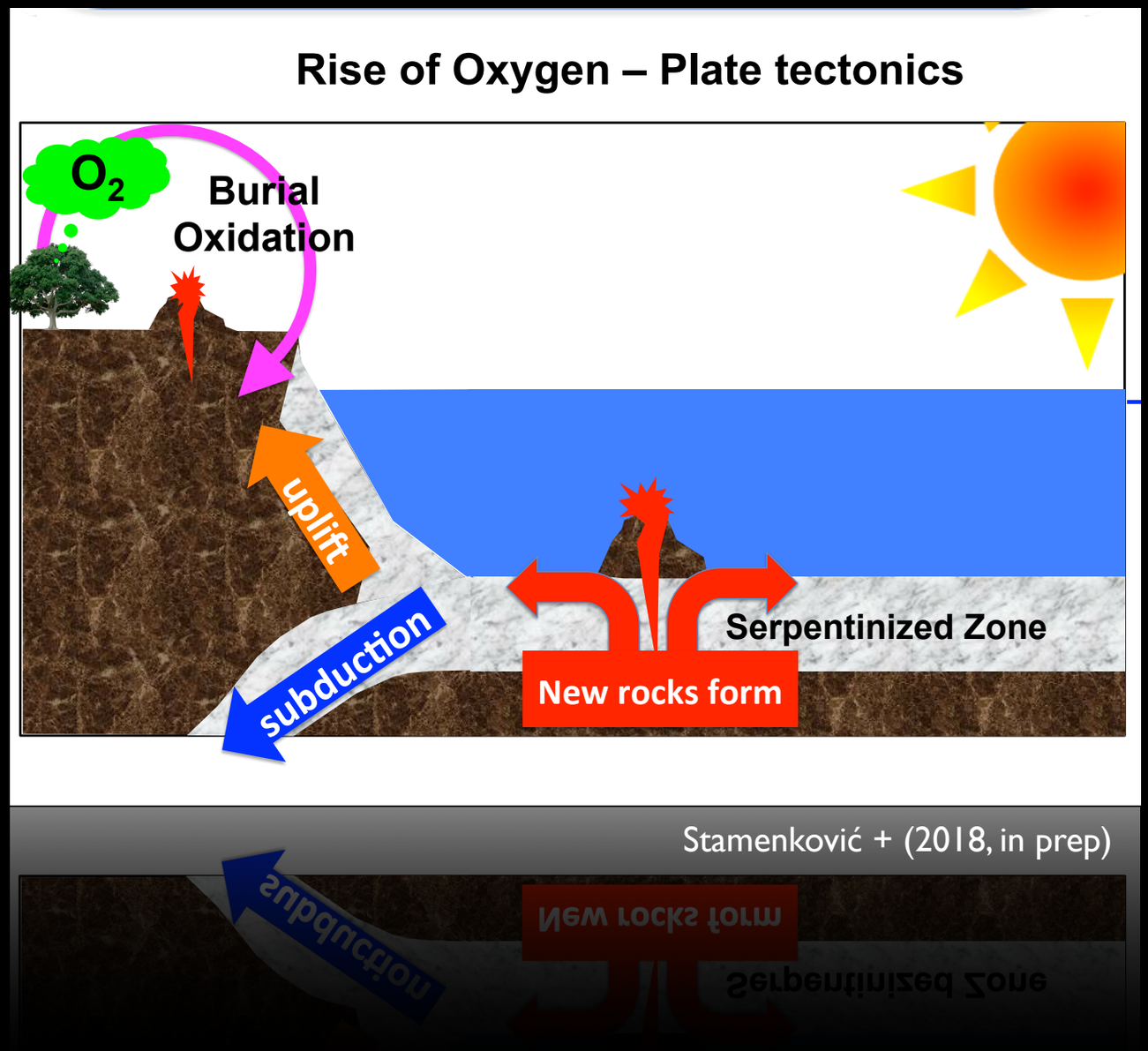
Stamenković + (2018, in review); Ward, Stamenković + (2018, in review)

"O_2 - plate tectonics" feedback?

- *Tectonic mode*
- *Redox (o): O_2*

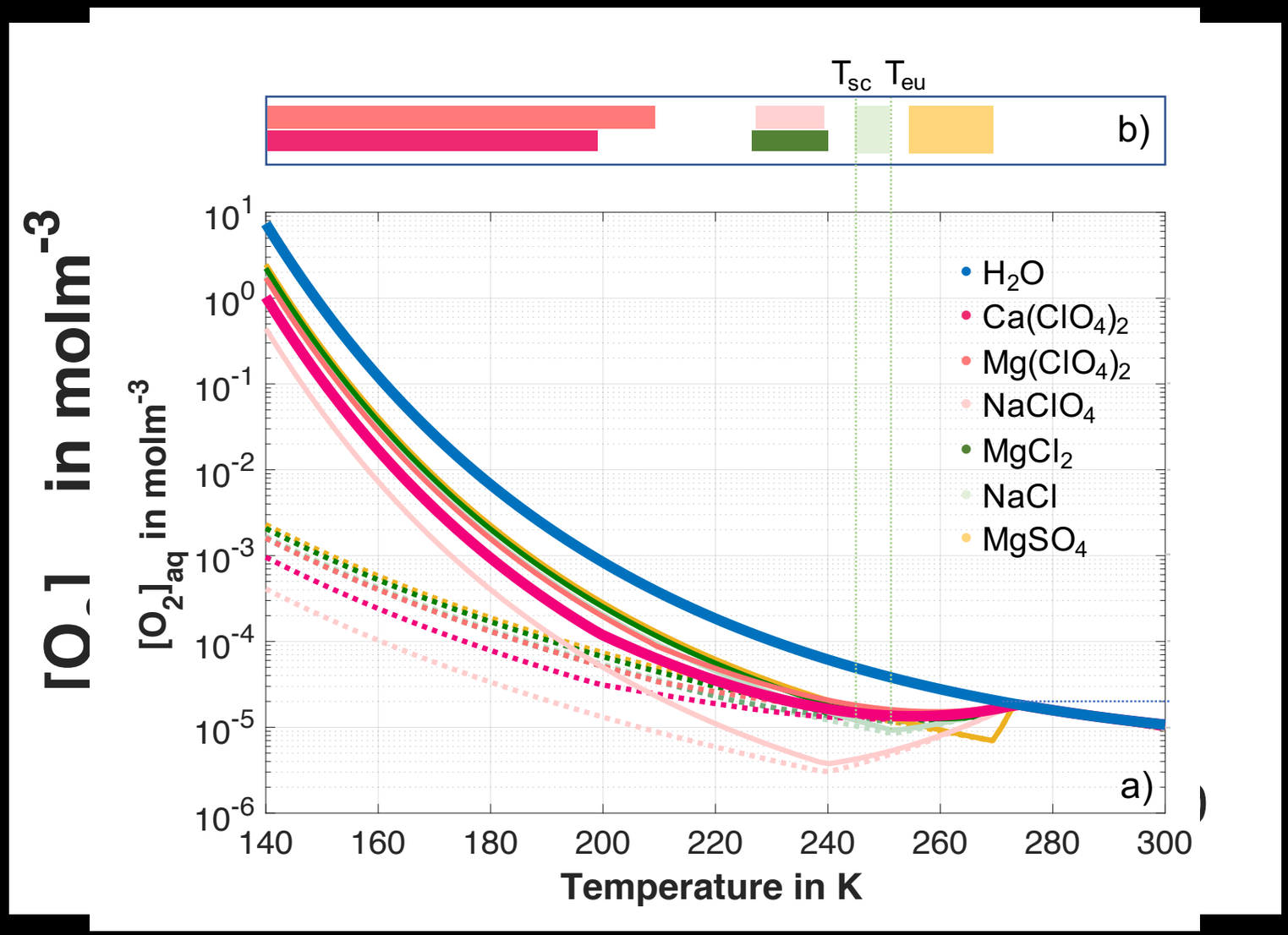


Stamenković & Seager (2016), Stamenković (2018, in prep)



How to oxidize rocks? An exotic example

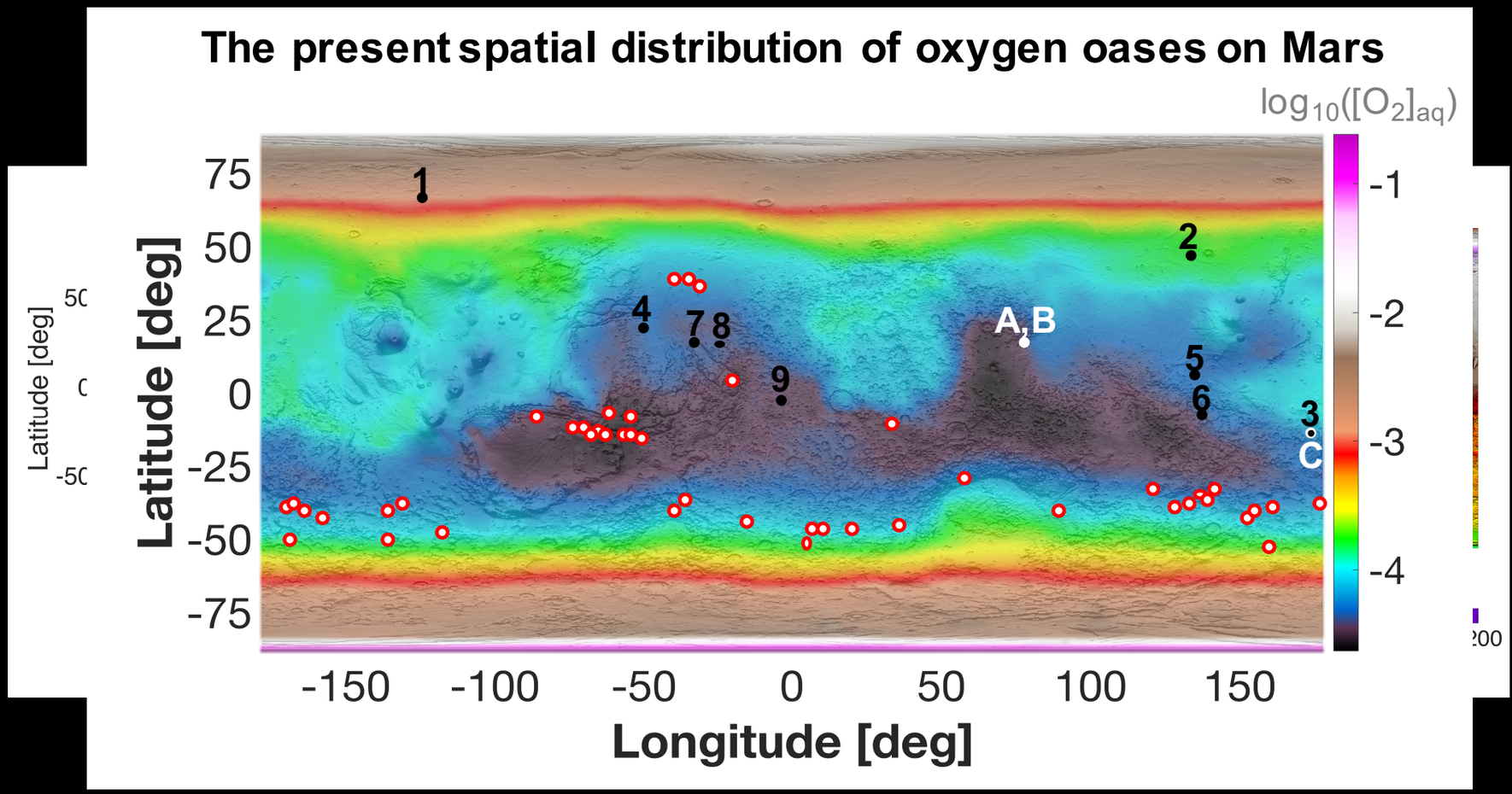
- *Tectonic mode*
- *Redox (o): O_2*



Stamenković + (2018, in review); Ward, Stamenković + (2018, in review)

O_2: Testing our Earth model on Mars

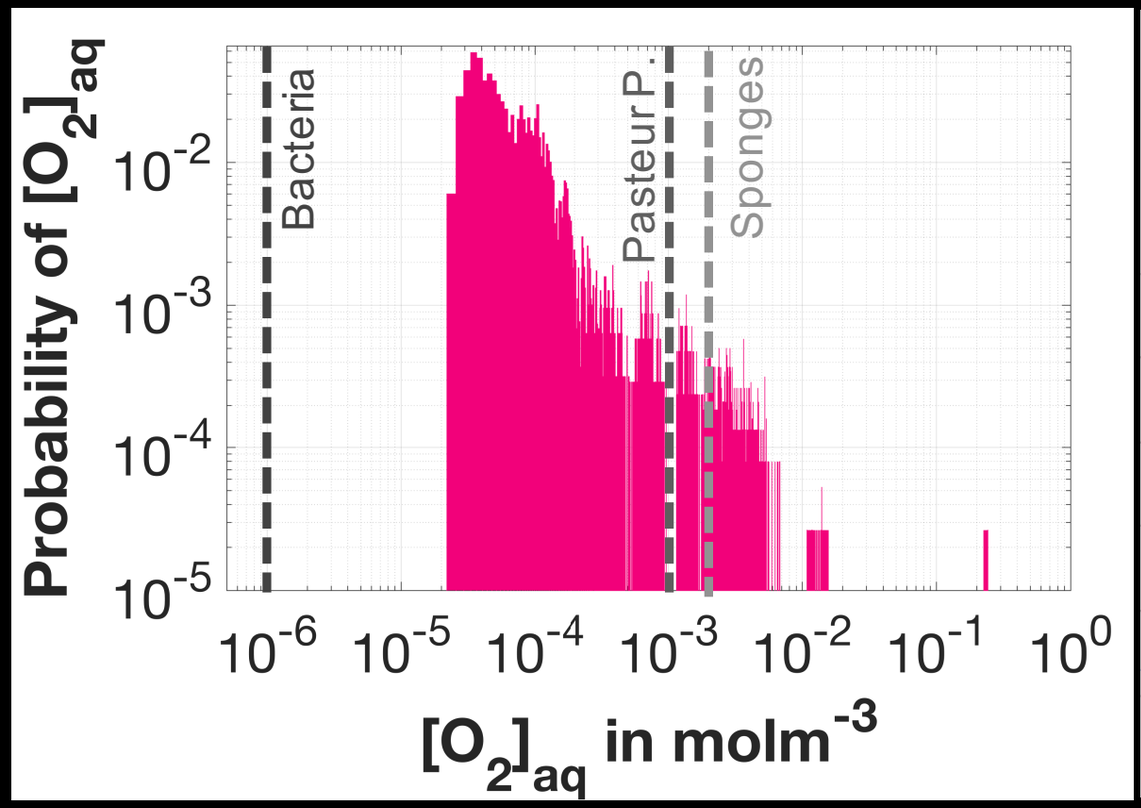
- *Tectonic mode*
- *Redox (o): O_2*

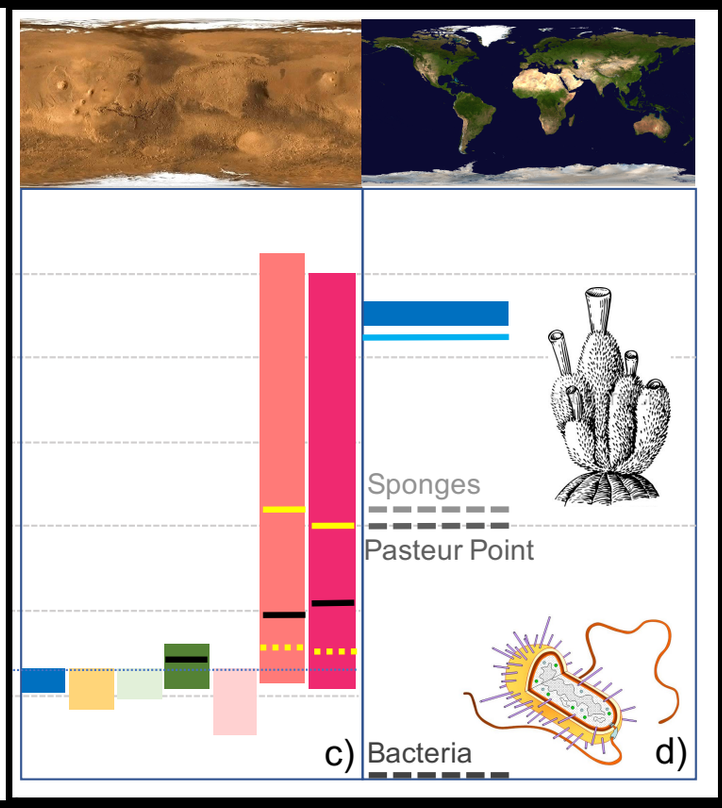


Stamenković + (2018, in review); Ward, Stamenković + (2018, in review)

O_2: Testing our Earth model on Mars

- *Tectonic mode*
- *Redox (o): O_2*

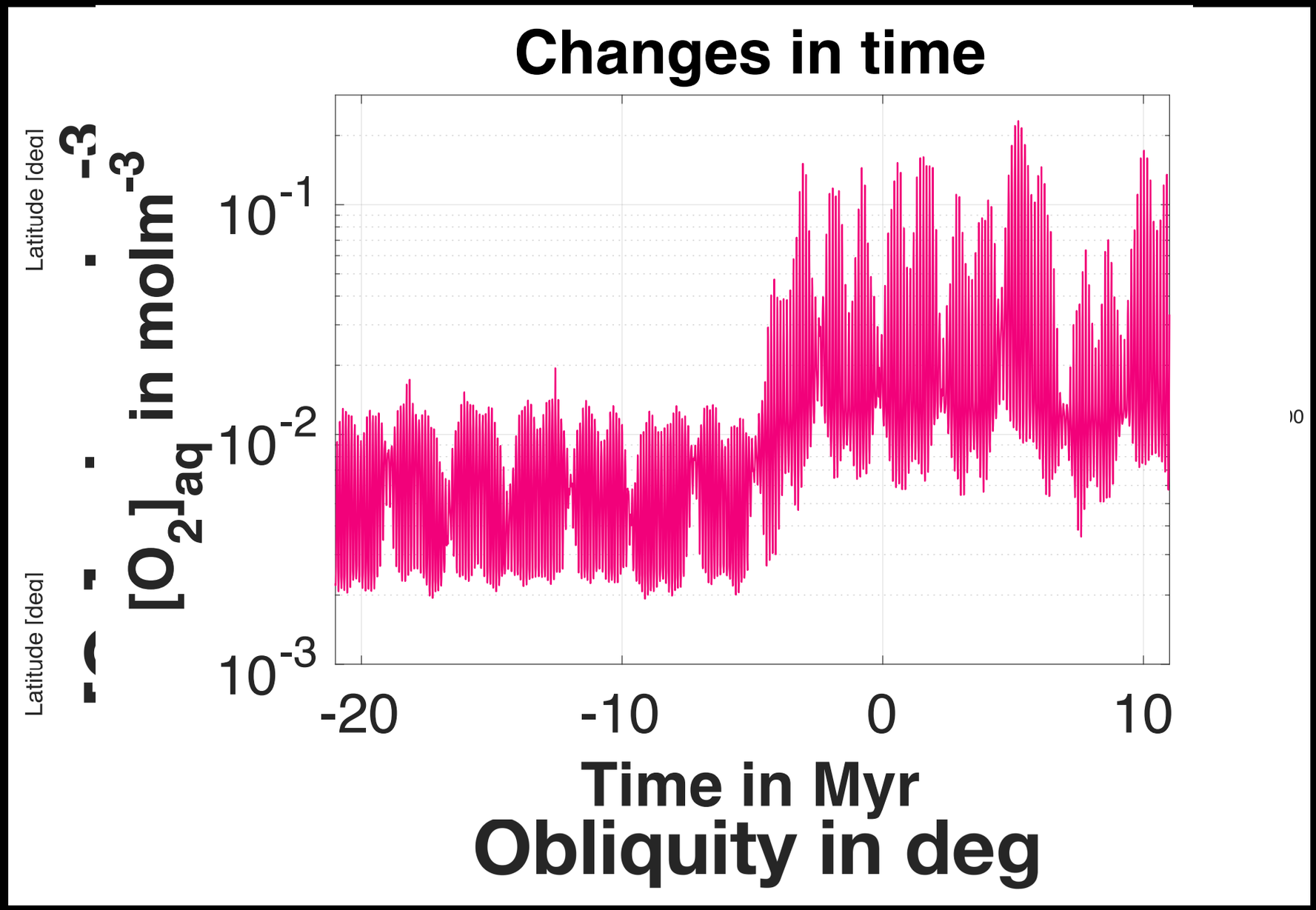




Stamenković + (2018, in review); Ward, Stamenković + (2018, in review)

O_2: Testing our Earth model on Mars

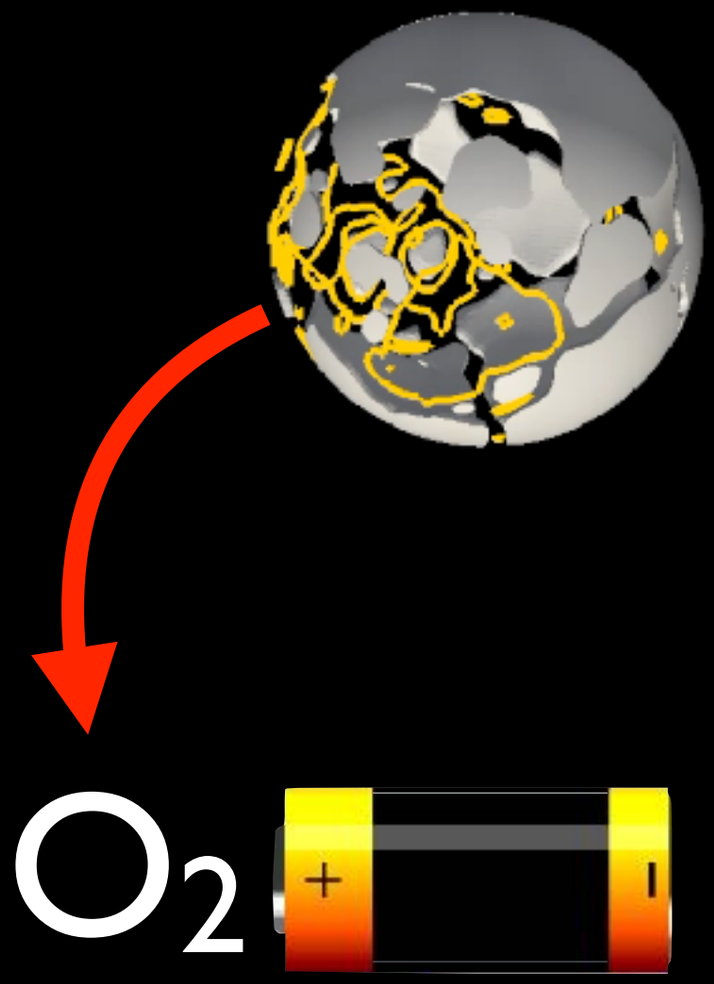
- *Tectonic mode*
- *Redox (o): O_2*



Stamenković + (2018, in review); Ward, Stamenković + (2018, in review)

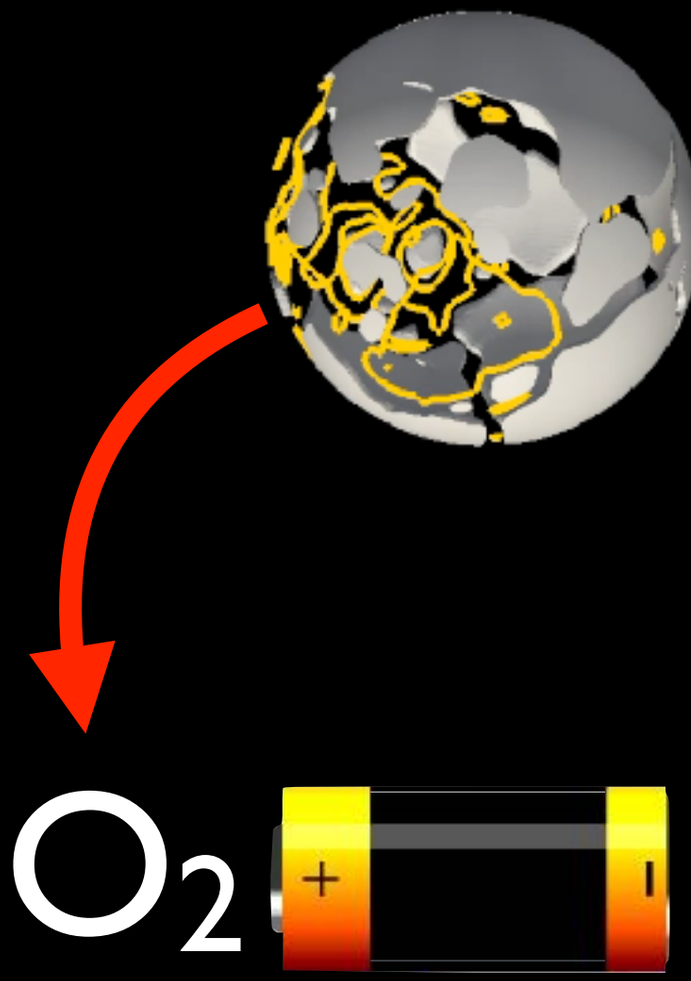
Towards oxygen

- *Tectonic mode*
- *Redox (o): O_2*



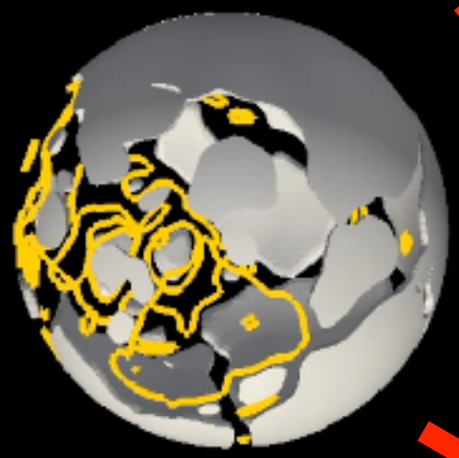
Towards oxygen

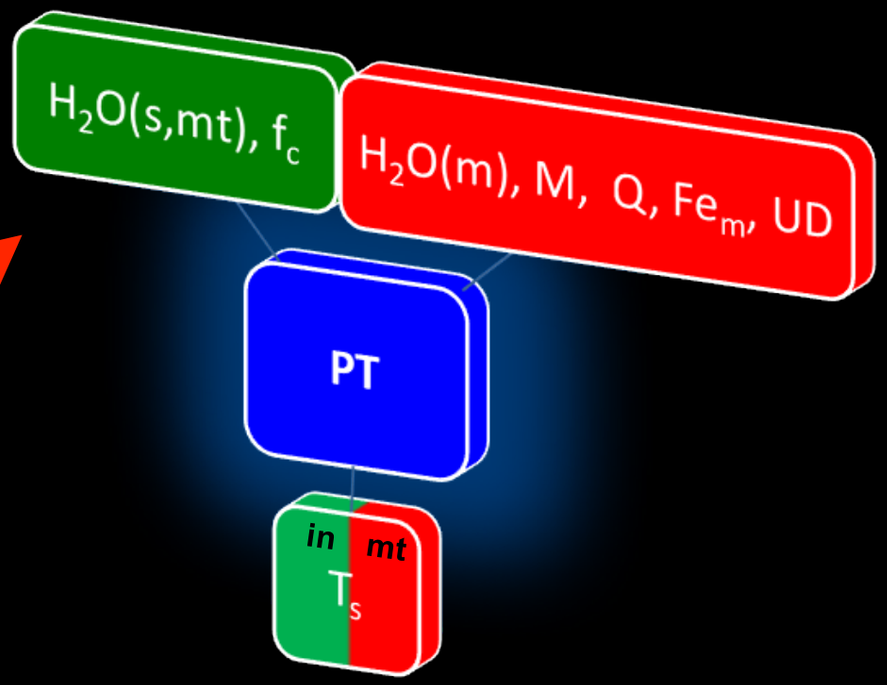
- *Tectonic mode*
- *Redox (o): O_2*
  - *Positive plate tectonics-O_2 feedback?*
  - *Aerobic oases without photosynthesis?*
  - *Mars is breathable today*
  - *We can test on Mars oxidation processes*

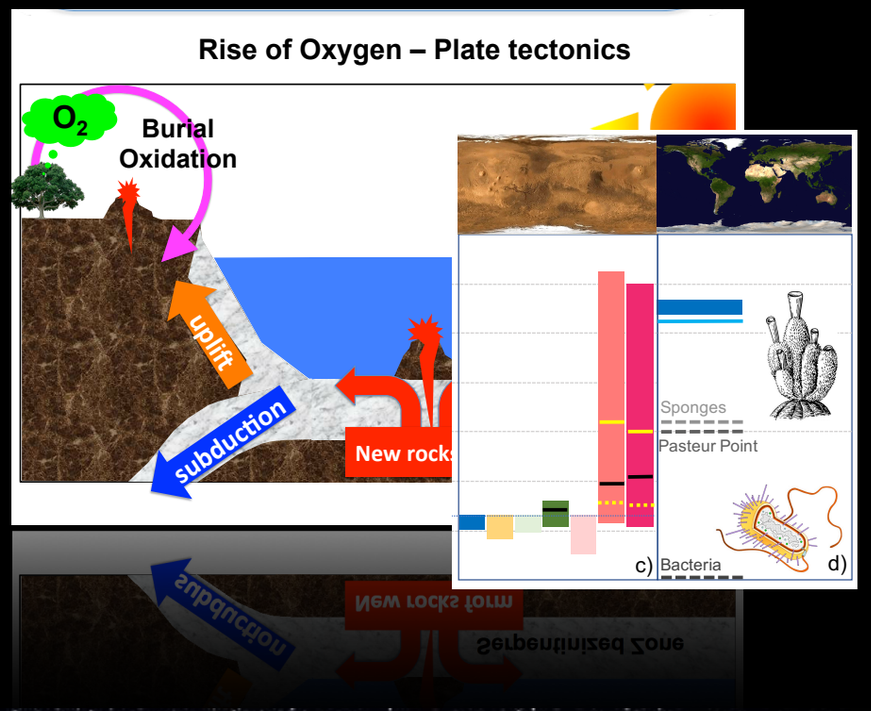


Part 2: Plate tectonics & O_2

- *Tectonic mode*
- *Redox (o): O_2*







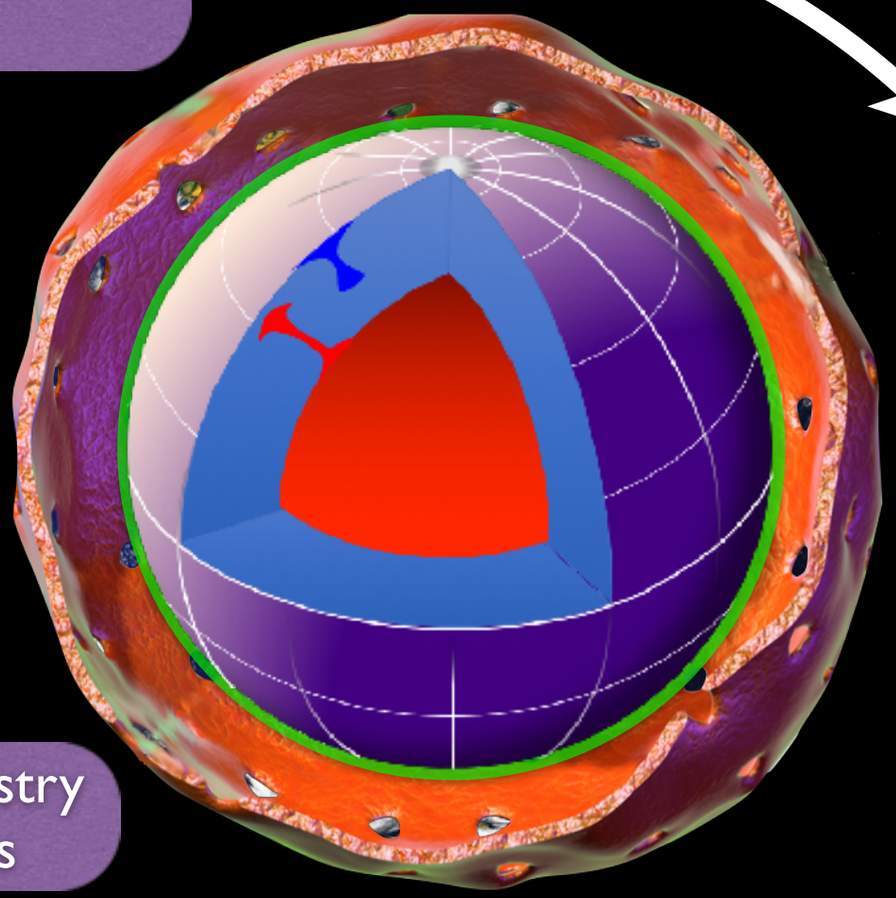
Conclusions

- Non steady-state processes critical for plate tectonics
  - *A bottom-up approach for plate tectonics? The lower mantle is driver.*
  - *Early start and self-regulation.*
  - *Water distribution is pivotal. Wet on top, dry inside, otherwise flop?*
  - *Asthenospheric channels enhance driving stresses.*
- We can now study oxygen-plate tectonics feedbacks and explore the formation of geophysics-climate-driven oxygen oases.
  - *Preliminarily results, but we find a positive feedback boosting rising O_2 levels.*
  - *Oxygen oases possible without photosynthesis of GOE.*
- We need to better understand oxidation processes.
  - *Modeling oxygen solubilities in various brines as a function of pressure and temperature shows surprising behavior that could allow on Earth and Mars oxygen oases without photosynthesis.*

Earth as a planet

Low-Temperature Outgassing: H_2, CH_4, H_2S

High-Temperature Outgassing: CO_2, SO_2/H_2S, H_2O



Thermal Evolution

Tectonic Evolution

Dynamo Evolution

Surface chemistry & processes

Climate

Life

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